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FINAL REPORT ~ FHWA-OK-18-04

RECYCLING AND REUSE OF MATERIALS IN TRANSPORTATION PROJECTS — CURRENT STATUS AND POTENTIAL OPPORTUNITIES INCLUDING EVALUATION OF RCA CONCRETE PAVEMENTS ALONG AN OKLAHOMA INTERSTATE HIGHWAY

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College Station, Texas

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of Transportation

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16. ABSTRACT

Oklahoma Department of Transportation (ODOT) is committed to protect and enhance human and natural environment while developing a safe, economical, and effective transportation system. The first objective of this research was to evaluate the availability of the recycled materials and develop strategies for increasing use of recycled materials in ODOT transportation construction projects. In this objective, an extensive literature search was conducted to acquire information pertaining to properties, current practices, and available field investigations of the commonly used recycled materials. Use of recycled concrete aggregate in concrete paving mixtures (RCA-CPM) was determined to be the major focus in this research as applications of RCA-CPM by ODOT and other DOTs have been reported as a sustainable and durable construction practice. Subsequently, a review of the key findings pertaining to RCA material properties and effects of RCA on portland cement concrete pavement (PCCP) performance was performed. Additionally, a life cycle assessment addressing all the three aspects of sustainability (i.e., economic, social, and environmental) was performed to do a comparative assessment between RCA-PCCP and plain PCCP and project the benefits of using RCA-CPM. The second objective was to evaluate the long-term performance of existing PCCP made with RCA in Oklahoma. A jointed plain concrete pavement (JPCP) and a continuously reinforced concrete pavement (CRCP) section were selected and evaluated through various tests covering different aspects, which includes visual survey, determination of mechanical properties, petrographic examination, and evaluation of the existing base through falling weight deflectometer (FWD). From the lab and field studies, it was verified that good base support, strong load transfer, and shorter joint spacing are essential design considerations for JPCP made of RCA-PCC. CRCP using effective anti-corrosion measures might be more suitable for implementing RCA-PCC; CRCP could better protect the base from erosion caused by higher differential energy and help restrain high drying and thermal volume change of RCA-PCC.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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EXECUTIVE SUMMARY

Like many other state departments of transportation (DOTs), Oklahoma Department of Transportation (ODOT) is committed to protect and enhance human and natural environment while developing a safe, economical, and effective transportation system. The state has great interests in using recycled and reusable waste materials, such as recycled concrete aggregate (RCA), reclaimed asphalt pavement (RAP), recycled tires, crushed glass, and recycled carpets, in infrastructural constructions.

This research consists of two objectives. The first objective was to evaluate the availability of the recycled materials and develop strategies for increasing use of recycled materials in ODOT transportation construction projects. In this objective, an extensive literature search was conducted to acquire information pertaining to properties, current practice, and available field investigations of the commonly used recycled materials. Use of recycled concrete aggregate in concrete paving mixtures (RCA-CPM) was determined to be the major focus in this research as applications of RCA-CPM by ODOT and other DOTs have been reported as a sustainable and durable construction practice. Subsequently, a review of the key findings pertaining to RCA material properties and effects of RCA on portland cement concrete pavement (PCCP) performance was performed. Additionally, a life cycle assessment addressing all the three aspects of sustainability (i.e., economic, social, and environmental) was performed to do a comparative assessment between RCA-PCCP and plain PCCP and project the benefits of using RCA-CPM. Researchers concluded that the use of RCA-CPM in PCCP could offer benefits covering all three aspects of sustainability such as cost savings, energy savings, conservation of good quality virgin aggregates, reduction in consumption of landfill space, reduction in greenhouse emissions, etc. These benefits are expected to be magnified in the future with a growing demand of environmental awareness and gradual reduction of good quality local virgin aggregate sources.

The second objective was to evaluate the long-term performance of existing PCCP made with RCA in Oklahoma. A jointed plain concrete pavement (JPCP) and a continuously reinforced concrete pavement (CRCP) section were selected and assessed through various tests covering different aspects, which includes visual survey, determination of mechanical properties, petrographic examination, and evaluation of the existing base through falling weight deflectometer (FWD). From the lab and field studies, it is verified that good base support, strong load transfer, and shorter joint spacing are essential design considerations for JPCP made of RCA-PCC. CRCP using effective anti-corrosion measures might be more suitable for implementing RCA-PCC; CRCP could better protect the base from erosion caused by higher differential energy (DE) and help restrain high drying and thermal volume change of RCA-PCC.

INTRODUCTION

Like other state DOTs, ODOT is committed to protect and enhance human and natural environment while developing a safe, economical, and effective transportation system. There are widespread benefits of using recycled and reusable waste materials (such as RCA, RAP, recycled tires, crushed glass, recycled carpets) in construction, especially in transportation projects. Currently, several technical studies to develop specification(s) and/or methodology to incorporate recycled materials in transportation construction projects are being conducted nationwide, but the development of specifications and/or methodology through research studies will only be effective if the involvement of the private sector (i.e., recycling industry, material suppliers, and construction industry) in decision-making process of implementing the technology (i.e., large-scale field applications) is well understood, encouraged, and recognized.

During the 1980s, ODOT constructed some sections of PCCP that contained RCA for all or a portion of the coarse aggregate. These existing sections offer a unique opportunity to evaluate the long-term performance of RCA concrete pavement in Oklahoma. With the increasing demand of using sustainable materials coupled with reduction in funding for maintenance and repair of our nation’s infrastructure, the use of RCA in concrete offers an effective way to both reduce cost and decrease the carbon footprint without compromising performance and service life if proper remedial measures (as needed) are taken.

OBJECTIVES

To address the above-mentioned issues in ODOT, the present research project was conducted with the following two main objectives:

- The first objective was to evaluate the availability of the potential recycled materials (e.g., RCA, RAP, recycled tires, crushed glass) and develop strategies for increasing use of recycled materials in ODOT transportation construction projects.

- The second objective of the study was to evaluate the long-term performance of two existing PCCP sections made of RCA-PCC in ODOT covering visual survey, determination of mechanical properties, petrographic examination, and evaluation of the existing subbase. The first section represents a JPCP portion made of RCA on I-40 in Oklahoma County between mileposts 165 and 173, which was constructed in 1984. The second section represents a CRCP section on I-35 (southbound) in Logan County between mileposts 147 and 152, which was constructed in 1989. The northbound CRCP section made of virgin limestone coarse aggregate between the same mileposts on I-35 has served as a control section.

This report includes the results of the availability of the potential recycled materials, strategies developed to increase the use of recycled materials, and insight gained for the long-term performance evaluation of the RCA concrete pavement sections in Oklahoma.

OBJECTIVE 1: EVALUATION OF RECYCLED MATERIALS AVAILABILITY AND DEVELOP STRATEGIES FOR INCREASING THE USE OF RECYCLED MATERIALS

The main purposes of this objective were to review the research and product literatures and survey agencies for:

- Assessing the current state/industry of practice on the use of recycling materials in transportation constructions.
- Developing strategies for increasing use of recycled materials in ODOT transportation construction projects.

The following tasks were conducted to achieve this objective.

Review of Commonly Available Recycled Materials and Their Current Industry Practice for Infrastructure Projects

Use of recycled materials including RCA, RAP, recycled asphalt shingles (RAS), recycled rubber, recycled glass, and recycled carpet, etc. replacing virgin aggregates in construction offer a more environment-friendly option with potential economic benefit. Based on a thorough literature review, information pertaining to properties, current practice, and available field investigations of the commonly used recycled materials is discussed below.

Recycled Concrete Aggregate

The Federal Highway Administration (FHWA) projected an increase in aggregate use to over 2.5 billion tons per year by 2020. It is also estimated that the annual production of construction waste from building demolition alone is approaching 123 million tons (FHWA 2004). According to FHWA (FHWA 2004), RCA (Figure 1) has been commonly used as base course in highway construction to increase the load capacity and facilitate better load distribution of the pavement. RCA, which is usually very angular and has irregular shapes, can also be incorporated to new concrete constructions as a concrete aggregate source, but the successful application of RCA in PCC requires a thorough understanding on the effects of its properties on the performance behavior.

Figure 1. Picture of RCA (FHWA 2004).

Current State of the Practice of Using RCA in PCC

According the FHWA (FHWA 2004), the use of RCA is restricted in nonstructural concrete such as curbs, gutters, and roadway barriers by many states. Some states require to know the source of the original aggregate of the RCA followed by a special approval of using RCA by the DOT. Typically, a comprehensive material characterization is required if the aggregate is from a non-approved source. The quality of RCA is source dependent, and the allowable levels of contaminants such as wood, clay, and steel rebar vary from state to state. The current state of the practice of using RCA in PCCP for different U.S. states are summarized (Cleary 2013):

- Texas:
  - Use approved sources.
  - Same gradation as natural coarse aggregate.
  - Allow 100 percent coarse RCA and up to 20 percent replacement by fine RCA for Class P concrete.
  - Free from frozen material and from harmful amounts of salt, alkali, vegetable matter, or other objectionable material, either free or as an adherent coating by washing.
  - Less than 0.25 percent by weight of clay lumps, 1.0 percent by weight of shale, 5.0 percent by weight of laminated or friable particles, and 18 percent magnesium sulfate soundness.
  - LA abrasion wear must not be more than 40 percent.
  - Use in class A (Inlets, manholes, curb, gutter, curb and gutter, conc. retards, sidewalks, driveways, backup walls, anchors), B (riprap, small roadside signs, and anchors), D (riprap), E (seal concrete), and P (concrete pavement) concrete.
- Colorado:
  - Same gradation as natural coarse aggregate.
  - Less than 3 percent by weight of clay lumps, 3 percent chert, 0.5 percent coal and lignite, and 12 percent sodium sulfate soundness.

  - LA abrasion wear must not be more than 50 percent.
  - Use as coarse aggregate for PCC, base courses, and sidewalks.

- Michigan:
  - Use approved sources.
  - Source variability allowance: specific gravity ±0.05, absorption ±0.40 percent.
  - After crushing, the resulting aggregate should be separated according to the original coarse aggregate type. Exceptions include:
    - Different aggregate types may exist in the same stockpile if the quantities by weight of each aggregate type retained on the No. 4 sieve do not differ by more than ± 10 percent from the average quantity obtained from at least three representative samples.
    - When aggregate is produced from concrete pavement with only one aggregate type that has been repaired with concrete patches with a different aggregate type.
  - Use as coarse aggregate for curb and gutter, valley gutter, sidewalk, concrete barriers, driveways, temporary pavement, interchange ramps, and shoulders.

- Alabama:
  - Use approved sources.
  - Same gradation as natural coarse aggregate.
  - When using RCA as gravel, a specific gravity of 2.55 or greater is required.
  - Free from adherent coatings by washing.
  - Less than 0.25 percent by weight of clay lumps (American Association of State Highway and Transportation Officials [AASHTO] T 112), 0.25 percent by weight of coal and lignite (visual), 2.0 percent by weight of shale (visual), and 10 percent sodium sulfate soundness.
  - LA abrasion wear must not be more than 50 percent.
  - Use as coarse aggregate in PCC or rip rap.

- Florida:
  - Use approved sources.
  - Same gradation as natural coarse aggregate.
  - Free from adherent coatings, metals, organic matter, base material, joint fillers, and bituminous materials.
  - Less than 2 percent by weight of clay lumps (AASHTO T 112), 1 percent by weight of coal and lignite (AASHTO T 113), and 2.0 percent by weight of soft and friable (AASHTO T 112).
  - LA abrasion wear must not be more than 50 percent.
  - Use as base or local material for stabilizing subgrade.

- Virginia:
    - Same gradation as natural coarse aggregate when RCA is used for open-graded mix.
    - Weight loss must not exceed 12 percent when subjected to magnesium sulfate
    - The amount of deleterious material should not be more than 0.25 percent by weight.
    - Less than 0.25 percent by weight of clay lumps (AASHTO T 112), 0.25 percent by weight of coal and lignite (AASHTO T 113), 12 percent magnesium sulfate soundness, and 5 percent when submitted to 100 freeze thaw cycles.
    - LA abrasion wear must not be more than 12 percent.
    - Not allow for:
        - Reinforced cement concrete.
        - In combination with other materials in contact with geotextile fabric when such fabric is used as a drainage item.
        - In backfill or bedding for perforated pipe.

Based on the information, Texas, Colorado, and Alabama allow use of RCA to make PCC slab other than conventional use in base and other low strength applications. Connecticut, Kansas, Minnesota, Wisconsin, and Wyoming have designed and built rigid pavements using RCA-PCC (discussed later). Michigan allows for temporary pavement, interchange ramps, and shoulders other than some low strength applications. Florida only uses for base or stabilizing subgrade. RCA is not allowed for reinforcement cement concrete by the Virginia DOT. This aspect is addressed in a later section where expert opinions on use of RCA to make PCC are summarized. RCA is not allowed to use in PCC in the following states: Arizona, Delaware, Georgia, Indiana, Kentucky, Louisiana, Maryland, Mississippi, Montana, Nebraska, Nevada. New Hampshire, New Mexico, Pennsylvania, Rhode Island, Utah and Washington.

Field Investigations of PCC Containing RCA

State highway agencies in Connecticut, Kansas, Minnesota, Wisconsin, and Wyoming successfully designed and built (1980–88) rigid concrete pavements containing RCA aggregates. In 1994, an extensive field survey with related laboratory and petrographic examination was conducted with the FHWA supports (Cuttell et al. 1997). In 2006, those studied project sites were revisited to generate long-term performance field data (Gress et al. 2009). During these two visits, 9 projects including 16 pavements section were examined. Table 1 shows the inspected pavement information. Based on the surveys, the following conclusions were made by the research groups:

- The higher the mortar content (old mortar adhered with the RCA) in RCA, the higher the cracking potential. CT1, MN2, WI1, WI2, and WY1 pavement RCA sections had low reclaimed mortar (RM) (less than 10 percent), and their performances were similar with the control pavements. In the MN 4 project, the mortar content of the RCA sections (old mortar fraction from the used RCA plus mortar in the new concrete) and control sections (mortar fraction in the new concrete) were 83.6 percent and 51.5 percent, respectively. The percent cracked slab observed in the field were 88 percent versus 22 percent in 1994 and 92 percent versus 24 percent in 2006. The higher percentage of cracked slab in RCA sections was believed to be caused by higher coefficient of thermal expansion (CoTE) of the RCA-PCC.

- In all cases except the MN 4 project, cores from RCA pavements had higher compressive strength (CS) compared to that for the corresponding control pavement section. This was because the RCA-PCC mixtures used lower water to cementitious materials ratio (w/cm). Besides, the Kansas and Wyoming projects used approximately 25 percent fine RCA. Researchers have shown that an adequate amount of fine RCA could even improve mixture's strength due to rehydration of the unhydrated cement particles in RM and improvements in the resulting total aggregate gradation (Snyder et al. 2018).
- Joint Spalling did not appear to be an issue related to the use of RCA in concrete.
- In the WY1 project, the RCA aggregates were produced from previously alkali-silica reaction (ASR) damaged pavement, but ASR mitigation techniques were used in the new construction. A moderate amount of ASR was identified by the uranyl acetate testing in 1994. In 2006, the RCA pavement showed some visual evidence of localized ASR surface cracking while the control one did not. However, the RCA pavement showed field performance equivalent to its control.
- The KS1, MN2, and MN3 projects used RCA from pavements, which showed sign of D-cracking. In 1994, no evidence was found in terms of recurrence of D-cracking in any of these reconstructed pavements. In 2006, again, the Minnesota pavements did not show any D-cracking problem. The success of using RCA from the D-cracked pavements to build new pavements with good performance is attributed to the precautions, such as using fly ash and reducing maximum aggregate size. However, the Kansas section showed re-appearance of D-cracking, which was taken care of by applying an asphalt overlay in 2002.

Table 1. RCA Pavement Information.

State	Year/Location	Pavement Type	Fine RCA Replacement	Control Section
Connecticut	CT1:1980-I-84-Waterbury	JPCP	25%	Yes
Kansas	KS1: 1985-K-7-Johnson Co	JPCP	25%	Yes
Minnesota	MN1: 1988-I-94 Brandon MN2: 1984-I-90 Beaver Creek MN3: 1980-US-59 Worthington MN4: 1984-US-52 Zumbrota	JPCP JPCP JPCP JPCP	No No No No	Yes No No Yes
Wisconsin	WI1: 1984-I-94 Menomonie WI2: 1986-I-90 Beloit	JPCP CRCP	No No	No No
Wyoming	WY1: 1985/1984-I-80 Pine Bluffs	JPCP	25%	Yes

In 1995, the TxDOT began to reconstruct a section of I-10 with CRCP containing 100 percent coarse and fine RCA in Houston (Won 2001). The project initially had problems with mix workability, due to contractors having difficulty in maintaining a consistent and uniform saturated surface dry condition. This obstacle was later overcome through a heightened awareness of the need to water RCA stockpiles and more frequent testing of the aggregate for moisture content. From a field survey 5 years after construction, it was concluded that:

- No distress including spalling, wide cracks, and punchouts have been taken place.
- Transverse crack spacing distribution of the RCA-PCC is comparable with conventional CRCP.
- The large amount of old mortar in the project did not appear to cause any negative effects.

The good field performance of CRCP containing RCA was likely attributed to the fact that the RCA-PCC had comparable CoTE and permeability relative to conventional PCC in this project. The low modulus of RCA concrete and good bond between RCA and new mortar also played roles.

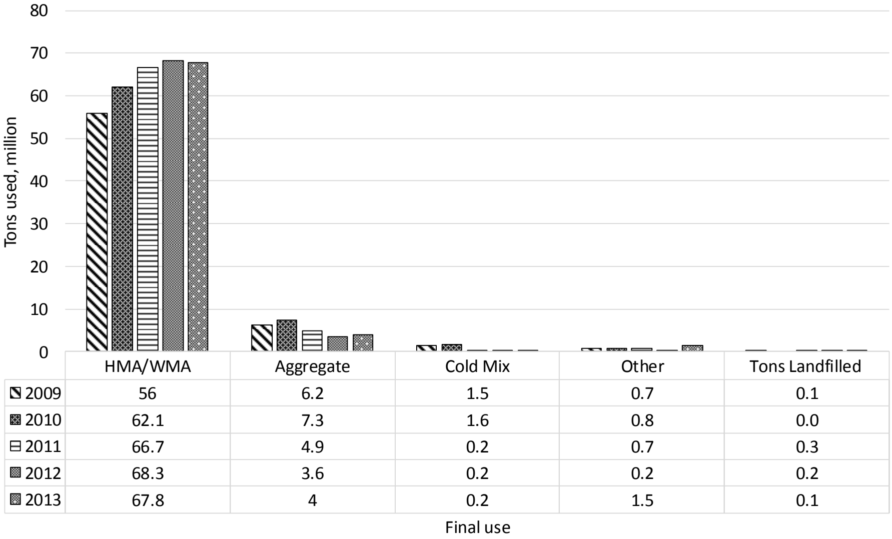
In 1986–1987, the Illinois DOT constructed a demonstration project on I-57 near Effingham, Illinois, to evaluate the feasibility of recycling an existing JPCP for use as virgin aggregate replacement in a CRCP surface course. In this project, 100 percent coarse virgin aggregate and 35 percent virgin sand were replaced by coarse and fine RCA, respectively. The pavement section was evaluated periodically. Based on the report in 2009 (Roesler and Huntley 2009), the following findings on this RCA pavement are summarized:

- Structural evaluation—Excellent load carrying capacity (less than 0.006-in. deflection under 9-kip load) and load transfer efficiency (LTE) across the transverse cracks were reported.
- Distress surveys:
    - Longitudinal cracking over the reinforcement bars in all lanes was identified: might be settlement cracking.
    - No deleterious ASR was detected, and the air void system was normal.
    - Mean transverse crack was shorter due to the greater drying shrinkage potential, slightly lower tensile strength, and reduced fracture properties of RCA.
- Functional Evaluation—Good skid resistance and fair-to-good ride quality were reported.

Recycled Asphalt Pavement

RAP (Figure 2) is a bituminous concrete material removed and reprocessed from pavements that need resurfacing or reconstruction. The reclaiming process can be either cold milling or full-depth removal followed by crushing. RAP is widely considered the America's most recycled and reused material. According to Hansen and Copeland (2015), the overwhelming majority of RAP is used in hot-mix asphalt (HMA) or warm-mix asphalt (WMA), followed by serving as base aggregate and being used in cold mix (Figure 3).

Figure 2. Picture of RAP (MnROAD, nd).



	HMA/WMA	Aggregate	Cold Mix	Other	Tons Landfilled
▧ 2009	56	6.2	1.5	0.7	0.1
▩ 2010	62.1	7.3	1.6	0.8	0.0
▤ 2011	66.7	4.9	0.2	0.7	0.3
▦ 2012	68.3	3.6	0.2	0.2	0.2
▦ 2013	67.8	4	0.2	1.5	0.1

Figure 3. RAP with Different Usage (Hansen and Copeland 2015).

The properties of RAP largely depend on the conditions of pavement from where it is reclaimed. There can be significant variation in the material properties due to the type of mix, quality and size of aggregate used, asphalt content, and asphalt mix consistency. RAP is usually finer than its original aggregate constituents due to the processing of the material. Typically, coarse RAP is produced by crushing and screening the material to ¼ in. to ½ in. in size (Griffiths and Krstulovich Jr 2002).

Recent Studies of PCC Containing RAP

Although RAP has been routinely used in HMA, most DOTs only allow the RAP fraction in the HMA up to 20 percent. Addition of RAP into an HMA mixture can alter the mixture properties significantly. Although no problems with mixing and compacting asphalt concrete mixture with RAP were found (Yamada et al. 1987), adding RAP increased void in mineral aggregate and void filled with asphalt (Daniel and Lachance 2005). Based on Li et al. (2008), asphalt concrete containing RAP had higher dynamic modulus than the control with greater influence at high temperature. The major concern that limits the use of RAP in HMA is that incorporation of high amounts of RAP may result in an overly stiff mixture. The overly stiff mixture not only can exhibit serious low-temperature cracking problem but also may crack prematurely when pavement is experiencing high deflections. Another issue of using RAP in HMA is related to producing low quality asphalt binder blends (i.e., virgin and RAP asphalt). The blended asphalt binder was more problematic especially when high amounts of RAP are introduced or RAP are blended with polymer modified binder (Copeland 2011).

Use of RAP as an unbound base material might be another construction strategy to reduce the volume of RAP stockpiles and facilitate sustainability. However, there are some potential problems as well. As a result, most states only allow a partial use of RAP and require RAP to be blended with virgin aggregates in the base. According to McGarrah (2007), 50 percent is considered a common maximum percentage for including RAP in an unbound base. When RAP percentage is higher, the blended material might have unacceptably low shear strength, resulting in a larger pavement deformation (Dong and Huang 2013). Besides, the time-temperature dependency and large variation of RAP properties add more difficulty in ensuring the quality of base. Furthermore, putting RAP in an unbound base layer possibly poses environmental risk due to leaching of chemicals. Although organic compounds do not leach from typical RAP, heavy metals such as chromium, lead, and barium are sometimes detected (Townsend 1998). Lead can exist in old RAP sources because of the traffic accidents and vehicle emissions. Pavements can be contaminated during gas spills since lead has been used in leaded gasoline and in crankcase oil for many years. Therefore, including RAP in a bonded material (such as PCC) might be the most environmentally friendly option.

Developing strategies to use RAP in PCC has become an increasing hot topic in the United States due to the increasing demands of sustainability. A successful use of RAP in PCC not only saves money for virgin aggregate, but also reduces virgin aggregate consumption and pollutions related to quarrying and processing of natural aggregate. Additionally, the use of RAP to make PCC facilitates disposing excess RAP and avoids the issues caused by RAP stockpiling (Shi et al. 2017). Several state DOTs and Toll Highway Authorities have supported projects related to use of RAP in making PCC (Berry et al. 2013; Brand et al. 2012; Mukhopadhyay and Shi 2017; Shi et al. 2017; Tia et al. 2012). Based on the previous works on the use of RAP in PCC conducted by researchers, the important findings are summarized:

- The addition of RAP into PCC invariably causes reduction in mechanical properties such CS, modulus of elasticity (MOE), flexural strength, and splitting tensile strength (STS). However, the effect on flexural strength is minimum (Shi et al. 2017).
- It is not recommended to incorporate fine RAP into PCC for pavement application because it will lead to unacceptable reductions on workability and mechanical properties (Mukhopadhyay and Shi 2017).
- PCC mixtures with dense aggregate gradation can be achieved by adding coarse RAP with adequate intermediate sized particles, which offer better overall performance in terms of workability and mechanical properties (Shi et al. 2017).

- Crack tends to propagate through asphalt layer in RAP-PCC (Figure 4). Asphalt is the major weak zone in RAP-PCC (Mukhopadhyay and Shi 2018). A longer and tortuous crack pattern indicates a more ductile behavior (Mukhopadhyay and Shi 2017).
- RAP-PCC has comparable or even better fracture properties relative to plain PCC (Shi et al. 2019).
- No significant durability issues have been reported for RAP-PCC (Mukhopadhyay and Shi 2017).
- The simulation work using finite element tools and Pavement ME Design models indicates that RAP-PCC's lower modulus and higher CoTE cause higher DE, which potentially induce higher base erosion and slab faulting. On the other hand, RAP-PCC's reduced modulus is effective to control CRCP crack width, which helps maintain a high LTE (Shi et al. 2018b).
- RAP-PCCP could yield sustainable benefits (Shi et al. 2018a).

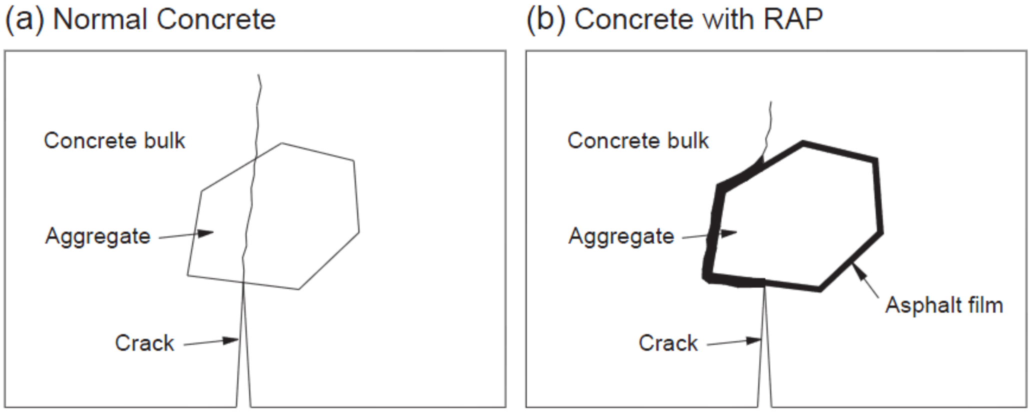


Figure 4. Propagation of Crack in Concrete with and without Asphalt (Huang et al. 2006): the Asphalt Existing in RAP Would Form a Thin Film at the Interface of Cement Mortar and Aggregate, and Crack Would Propagate along the Mortar-Asphalt-Aggregate Interface Rather than Break the Aggregate, Resulting a Dissipation of More Energy.

Field Investigations of PCC Containing RAP

There are very few examples of making single-lift RAP-PCC field sections in the United States. This is probably due to the speculation that single-lift RAP-PCC slab may not be able to satisfy the requirements of mechanical properties, durability, and surface characteristics. Adding an extra bin to handle RAP aggregate in the concrete mixing plant was found to be another obstacle in some circumstances. A detailed literature review indicates that Montana might be the only state that had experience in building single-lift RAP-PCCP. In 2012, two demonstration sections with 10-in. RAP-PCC slabs using HR mix (100 percent coarse RAP and 50 percent fine RAP replacement) for one section and HS mix (50 percent coarse RAP and 25 percent fine RAP replacement) for the other section were placed at the MSU/WTI Transcend Research Facility. Material production and slab construction using conventional equipment were conducted successfully without any issues. None of the slabs from both the sections showed any observable damage (cracking or spalling), excessive shrinkage, or curling during a two-year monitoring period (Berry et al. 2015). In 2010, the Illinois Toll Highway Authority constructed a 9-in. thick concrete slab with 28 percent washed, coarse fractionated RAP and overlaid by a 3-in. thick HMA as part of the Milwaukee Avenue ramp construction. The concrete was produced with 655 lb/cy of cementitious content, including 79 percent of cement and 21 percent of fly ash. This innovative construction provided a viable way to enhance sustainability with no negative impacts on cost and performance (Bentsen et al. 2013).

The use of RAP-PCC in the bottom lift of a two-lift pavement construction can date back to the 1970s. Iowa DOT constructed a two-lift trial section with an 11-in. composite section (7-in. lower course and a 4-in. upper course). The lower course used RAP and RCA as aggregate sources. Based on the field experience, the investigators believed that using existing concrete on reconstruction projects as an aggregate source can be feasible (Bergren and Britson 1977). Kansas built a two-lift construction with RAP to replace the intermediate sized well gravel at 15 percent of the total aggregate in the 7 in. bottom lift in the 1990s. The top lift was 3 in. and was placed with the standard control mixture. Until 2011, no major distresses were observed (Rao et al. 2013).

After building the RAP-PCCP with an HMA overlay, the Illinois Tollway built another two-lift composite concrete pavement containing dirty fractionated RAP. The pavement was placed on the Reagan Memorial Tollway (I-88) in 2012, and the total thickness was 11.25 in. The contractor used a ternary concrete mixture with 35 percent supplementary cementitious material and 20 percent dirty fractionated RAP with an optimized aggregate gradation for the bottom lift, which was covered by a standard virgin aggregate non-ternary PCC layer.

Some of the European countries such as Switzerland, Belgium, the Netherlands, France, Austria, and Germany have applied the two-lift construction much more common than in the United States (Rao et al. 2013). In particular, Austria built the entire 200 miles of A1 freeway with 10 percent RAP in the lower lift and the pavement was reported to perform well after 20 years (Rao et al. 2013). A unique roller compacted concrete with RAP and steel fibers has been designed and tested through accelerated pavement testing and experimental filed test section in France (Bilodeau et al. 2011). The studied fiber reinforced roller compacted concrete mixtures with RAP aggregates contained varying RAP percentage (0, 36 percent, and 70 percent by total dry mixture volume) and 25 kg/m^3 of hooked steel fiber. The accelerated pavement testing of the sections built with fiber-reinforced roller-compacted concrete (FRCC) containing RAP after 2.3 million of the 65 kN standard wheel load showed no significant structural damage caused by the addition of RAP.

Besides constructing pavement slabs, RAP-PCC was used for some other low strength applications. For example, the Maine Department of Transportation blended portland cement, RAP milled from the highway, and virgin aggregates to reinforce and stabilize road shoulders adjacent to the existing old concrete slabs in 2001. This innovative method turned out to be very successful, provided the shoulder preservation and stabilization is a major concern of the design and the extra cost is considered worthwhile (Thompson 2007).

Recycled Rubber

An estimated number of one billion scrap tires have been disposed of in huge piles across the United States. An additional 250 million tires unaccounted for are discarded yearly

(RMA 2011). Recycled tires were widely used in embankments and road beds by employing baling and shredding methods. The use of tires specifically detailing efforts with the use of baling has been reported by Zornberg et al. (2005), which is considered a safe and economical way to use scrap tires. For pavements, it is feasible to use the bales to create mats over very soft foundation soils and to provide insulation to reduce frost action. When mixing rubber with soil, the shear strength of the mixture can be improved, and the unit weight is reduced. A priority list of highway applications includes use in low embankment systems, providing structural elements in slope repairs and embankment on soft ground subgrades and enhanced drainage. Rubberized concrete is a construction material that contributes greatly to the development of civil engineering sustainability by using industrial waste and reducing natural resource consumption (Li et al. 2004). Concrete with recycled rubber can be used in various civil constructions such as concrete floors, walls, and roof tiles (Fattuhi and Clark 1996; Li et al. 2004; Siddique and Naik 2004). Studies (Khaloo et al. 2008; Turatsinze and Garros 2008) have shown that the concrete with recycled rubber (Figure 5) has enhanced toughness and resistance of moisture migration through the material and improved thermal insulation, sound absorption, and low density. However, a loss of the CS for the addition of recycled rubber is a major problem. Some examples of the research examining the use of recycled rubber in transportation are:

- The Carson City, Nevada, company markets a noise wall that contains recycled rubber tires; it also has researched the use of rubber tires in lightweight fill, subgrade insulation, and channel slope protection as well as an additive to PCCP.
- The North Carolina DOT conducted a laboratory study on the use of ground scrap tires in PCC (Hesham et al. 1993). The scrap tires are grounded after the loose steel and fibers were removed. The ground rubber replaced fine aggregate in the concrete mixture at the 10 percent, 20 percent, and 30 percent replacement levels. Based on the test results, the concrete's CS and flexural strength both decreased with the increasing amounts of rubber.
- In 1992, a project conducted in Maine assessed the effectiveness of using tire chips as an insulating layer to control frost penetration beneath a gravel-surfaced road that experienced severe deterioration during spring thawing. Researchers found that a 152-mm-thick tire chip layer can reduce frost penetration by up to 40 percent (Humphrey and Eaton 1993).

Figure 5. Picture of Recycled Rubber.

Recycled Glass

Waste glass is a major component of the solid waste stream in many countries and is considered a 100 percent recyclable material (Meyer 1999; Meyer and Baxter 1997; Meyer and Xi 1999). The waste glass can be found in many forms, including container glass, flat glass such as windows, bulb glass, and cathode ray tube glass. According to Bolden et al. (2013), 11.5 million tons of glass in the Municipal Solid Waste stream was generated in the United States in 2010. Glass waste is hard to break down if it is landfilled; the whole process can take over a million years. Ismail and Darwish (2014) recently produced glass modified concrete with recycled glass to replace 25 percent of coarse aggregate that has similar compression strength with traditional concrete. Additionally, use of glass to replace virgin aggregates in concrete can potentially produce high-quality concrete in the future. However, glass cullet can result in workability problems in concrete mix and the likelihood of ASR. Because of this, waste glass is often grounded to powder and serves as a cement replacement in PCC. Shao et al. (2000) showed that ground glass having a particle size finer than 38 µm could exhibit a pozzolanic behavior; the concrete containing ground waste glass had satisfied strengths. For the application in HMA, glass is difficult to bond with asphalt and therefore can cause stripping and raveling problem.

Recycled Carpet

According to Carpet America Recovery Efforts in 2010, landfilled carpet waste was 338 million pounds and 271 million pounds were recycled in composite lumber (both decking and sheets), tile backer board, roofing shingles, rail road ties, automotive parts, carpet cushion, and stepping stones. Three million pounds were used for alternative fuel and 23 million pounds for cement kilns (Bolden et al. 2013). Carpet fiber can be used to reinforce concrete. Just like other types of fiber reinforced concrete, carpet fiber reinforced concrete could have improved toughness and tensile properties Wang et al. (2000). Reduction of shrinkage and improvement in fatigue strength, wear resistance, and durability can also be achieved when carpet fiber is added into concrete.

Sulfur By-products

Brimstone is one of the major by-products from the oil and gas industries; it is essentially elemental sulfur. Sulfur also exists in the form of sulfuric acid, and sulfuric acid is a by-product of ferrous and nonferrous metal smelting. Sulfur can serve as a binder to produce construction materials such as sulfur-extended asphalt and sulfur concrete. For the concrete application, sulfur is usually substituted for the more expensive portland cement. Starting in the early 1990s, sulfur has been commonly mixed with polymers and aggregates to produce sulfur polymer concrete with a major application as a rapid repair mix and to encapsulate hazardous materials (Mattus and Mattus 1994). Table 2 summarizes the advantages and disadvantages using sulfur in transportation constructions.

Table 2. Advantages and Disadvantages Using Sulfur in Transportation Constructions (Stroup-Gardiner and Wattenberg-Komas 2013).

Advantages/ Disadvantages	PCC	HMA
Advantages	• Gained strength rapidly (~80 percent within a few hours of placement) • Resistant to acids • Durable in corrosive environments • High density • Resisted cracking • Resisted plastic deformation	• Increased stiffness without becoming brittle at cold temperatures • Allowed the use of softer, lower viscosity asphalt cements to be used in cold climates while minimizing rutting problems during hot summer seasons • Better performance than conventional HMA in extremely hot or cold climates • Improved the overall structural capacity of the pavement system • Could be reheated since the hardening process is thermosetting • Potential for reducing pavement thickness and therefore cost • Performance appeared to be comparable to conventional HMA
Disadvantages	Required modifications to field mixer to provide heated material on-site (sulfur polymer concrete)	• Worker safety concerns because of formation of hydrogen sulfide or sulfur dioxide gas if mixing temperature is too high • Sulfur mix becomes difficult to work with at temperatures greater than 320°F owing to increased viscosity • Although not flammable on its own, sulfur still meets the criteria of USDOT of a hazardous material

Recycled Plastic

Plastics such as scraps of small strips of high-density polyethylene can be used to reinforce soils in structural fills in terms of improving soils strength and stiffness (Benson and Khire 1994). Compared to the conventional soil reinforcement, plastics can be comingled and require little processing besides shredding.

Coal By-products

Coal combustion by-products are produced from the fossil fuel used in electric power generation, which accounts for about 50 percent of the electricity demand in the United States.

Different by-products can be obtained from different locations of a typical steam generating system. According to Stroup-Gardiner and Wattenberg-Komas (2013), these coal combustion by-products include:

- *Bottom Ash*—collected from the bottom of dry-bottom boilers and its size ranging from the size of fine gravel to fine sand. The material is heavier than fly ash with the major components are similar to the boiler slag (Butalia and Wolfe 2000; EPA 2005).
- *Boiler Slag*—obtained from molten ash collected in wet bottom boilers where the molten ash is water cooled. The molten ash shatters into black angular pieces that have sizes similar to coarse sand to fine gravel and have a smooth appearance. The major components are silica, aluminum, iron, and calcium (Butalia and Wolfe 2000; EPA 2005).
- *Fly Ash*—entrained particles in the exhaust gases leaving the combustion chamber. This consists of the finest particles collected from coal burning processes. The major components are also similar to those found in boiler slag and bottom ash.

RCA Material Properties and Their Effect on PCCP

A questionnaire was sent to the identified experienced and knowledgeable representatives from the ODOT to inquire the general interest of using different recycled materials and potential challenges of using these materials in Oklahoma infrastructural projects. Based on the survey results (presented in Appendix A), a decision was made to narrow down the focus of this research to use of RCA as an aggregate replacement for pavement applications. Another survey questionnaire was then sent to nationally recognized experts to acquire insights and experience on use of RCA in PCC. Based on the collected survey results (presented in Appendix B) together with the literature review findings, a summary of RCA material properties and effects of RCA on PCCP performance is presented in this section. This section only highlights the key findings on this topic; it is not intended to provide an exhaustive review of this topic as such information can be obtained from several existing publications:

- Anderson, K. W., Uhlmeyer, J. S., and Russell, M. A. (2009). "Use of recycled concrete aggregate in PCCP: literature search." *Report WA-RD 726.1*, U.S. Dep. of Transportation, Washington.

- FHWA (2004). “Transportation applications of recycled concrete aggregate," Federal Highway Administration, Washington, D.C.
- Reza, F., and Wilde, W. J. (2017). “Evaluation of recycled aggregates test section performance.” *Report MN/RC 2017-06*, U.S. Dep. of Transportation, Minnesota.
- Snyder, M., Cavalline, T., Fick, G., Taylor, S. K., and Gross, J. (2018). “Recycling Concrete Pavement Materials: A Practitioner’s Reference Guide.” Federal Highway Administration.

RCA Properties

Aggregate properties have profound effects on concrete properties. Due to the existence of the RM in RCA, the properties of RCA can be significantly different from those for the virgin aggregate. The RCA properties are summarized below.

Specific Gravity

The existing literatures invariably concluded that RCAs have lower specific gravity compared to the commonly used virgin aggregates. It is reported that the specific gravity of RCA is usually 5–15 percent lower than that of natural aggregate (Choi and Won 2009; Fathifazl et al. 2009; Limbachiya et al. 2000; Otsuki et al. 2003; Ravindrarajah 1987; Wathne 2012). The RM portion in RCA is lighter (porous) than the original aggregate, which causes reduction of RCA density (Gress et al. 2009).

Water Absorption

Because RM has greater porosity that can hold more water in the pores (McNeil and Kang 2013), almost all researchers have reported that RCA has higher water absorption relative to virgin aggregate (Choi and Won 2009; Fathifazl et al. 2009; Otsuki et al. 2003; Ravindrarajah 1987; Wathne 2012). According to Appendix B, concrete producers must maintain moisture levels near or above saturated (i.e., saturated surface-dried [SSD]) in RCA prior to batching. Due to higher than normal absorption rates in the RCA, research has demonstrated the need to soak the aggregates prior to use. In the O’Hare Airport project, the concrete producer followed recommendations to maintain a high moisture content in the RCA, and the application of RCA in PCCP was very successful (David Lange). Compared to natural aggregates, one should pay more attention on the absorption time of RCA. Although it does not require special equipment and the procedure is similar than what is adopted for natural aggregates, some additional time is required (Leandro Francisco Moretti Sanchez). Additionally, when RCA is wet when batched, it can provide a source of internal curing, which enhances hydration of the new paste system (Snyder et al. 2018). It is suggested that RCA’s potential internal curing properties should be investigated (Richard Meininger).

Abrasion Resistance

The abrasion resistance of RCA has been evaluated by various research teams through the Los Angeles abrasion test. As expected, RCA has higher LA abrasion loss (i.e., lower abrasion resistance) compared to the virgin aggregate (Ravindrarajah 1987; Sagoe-Crentsil et al. 2001; Shayan and Xu 2003; Tavakoli and Soroushian 1996; Wathne 2012). This is because the RM can break off easily along the interfacial transition zone (ITZ) during the abrasion test. Besides, aggregates in RCA can be weaker than the virgin aggregate as well due to the potential microcracks developed during the pavement service life and the RCA processing stage.

Coefficient of Thermal Expansion

The CoTE of RCA is usually higher than its virgin aggregate because mortar has higher CoTE value than aggregate. The existing lab measurements confirmed this finding (Cuttell et al. 1997; Gress et al. 2009; Roesler and Huntley 2009; Snyder 2016; Wathne 2012).

Sulfate and Magnesium Soundness Loss

According to Choi and Won (2009) and Wathne (2012), RCA has lower sulfate soundness than the virgin aggregate. The magnesium soundness of RCA might be comparable with the virgin aggregate (Wathne 2012).

Reclaimed Mortar Content

The above-mentioned findings clearly indicate that the RM of RCA is a key component that affects RCA properties. An RCA source with lower reclaimed mortar content (RMC) is more likely to have fewer deviating properties with virgin aggregates. Therefore, the RMC of RCA is considered an extremely important indicator of RCA properties.

The RMC can be determined based on a method proposed by Fathifazl et al. (2009). In their method, the oven-dried RCA samples were first weighted (W_{org}) and then immersed in sodium sulfate solution with 26 percent weight concentration for 24 hours. The RCA samples are subsequently subjected to five freezing-thawing cycles (a cycle include −17°C for 16 h and 80°C for 8 h). The conditioned samples are fully washed and then oven dried for 24 h at 105°C. The mass of the samples was measured and weighted as W_{con}. The RMC is then calculated as:

$$RMC = \frac{W_{org} - W_{con}}{W_{con}} \times 100\%$$

Besides the above-mentioned approach, thermal treatment method (De Juan and Gutiérrez 2009; Yonezawa et al. 2001) and petrographic method (Gress et al. 2009) can also be used to test the RMC of RCA. While the selection of the best test method for a specific RCA source is largely dependent on good engineering judgement by considering facility availability and RCA mineralogy, the petrographic method might be the most accurate option because the sample preparation creates little defect; one common problem of the other methods is that they might not be able to completely remove the RM or the processes involved might deteriorate the aggregate as well. In addition, the petrographic analysis provides an opportunity to acquire detailed information on mortar distribution around each individual aggregate.

The RMCs determined by several researchers using the above-mentioned techniques and RCA from various sources were found to be varied from 25 to 75 percent (De Juan and Gutiérrez 2009). The RMC of RCA is highly related to the RCA processing, more specifically, the type of crusher used in producing RCA. Impact crushers are more effective at removing RM, but they usually produce lower amount of RCA from any given amount of concrete. Using jaw crushers generally yields a higher RCA quantity, but the RMC is higher compared to RCA produced with impact crushers (Snyder 2016). According to Appendix B, it is a common practice that the primary crushing of RCA is done with a large jaw crusher and that impact crushers are best as secondary crushers at shattering the concrete and extracting any steel ahead of final screening and removing of any steel with magnets and/or by manual picking (Richard Meininger).

According to Gress et al. (2009), field sections built with RCA with higher RMC had worse performance compared to the pavements containing RCA with lower RMC. However, some experts believe that RM will not be a problem because if the mortar survives the crusher, then the bond between the mortar and rock is excellent and should not create any negative issues in terms of strength (Appendix B). The negative effect caused by RM (e.g., higher absorption, shrinkage, and CoTE) could be taken care of from mix design and pavement structure design.

Surface Characteristics and Gradation

The surface characteristics and gradation of RCA have significant effects on workability and strength of the produced PCC. While Sagoe-Crentsil et al. (2001) stated that RCA has more rounded, spherical shape because that RM can smooth out the angularity of virgin aggregate, most of the researchers found that RCA is more angular than virgin aggregate (Ravindrarajah 1987; Wathne 2012). The inconsistency of the findings might be caused by the varying methods used to produce RCA and the surface characteristic of the virgin aggregates. The crushing and processing procedures also influence the gradation of RCA.

RCA-PCC Mix Design

While limiting the amount of RMC in RCA is considered the most effective way to improve RCA-PCC properties, it is usually impractical to eliminate all the RM, so the changed properties of RCA due to the presence of RM require care and provision in designing PCC containing RCA. The common practice for the existing field sections was replacing virgin aggregates with RCA on the volumetric basis without accounting for the RM. This approach failed to consider the effect of old mortar in the mix design, which might result an increase in the total mortar content and caused increasing slab cracking (Gress et al. 2009).

Fathifazl et al. (2009) proposed an equivalent mortar volume concept by considering the RM in coarse RCA as part of the total mortar content. They assumed that only good quality RM portions (i.e., sound mortar having good bond with the original aggregate) survive after crushing and processing, so both reclaimed and fresh mortars behave the same way in concrete and do not cause any measurable difference in concrete properties. Using this approach, researchers were able to generate RCA-PCC with fresh and hardened properties similar to plain PCC while significantly reduced cement and fine aggregate content in the RCA-PCC mixture.

However, these mixtures tend to be harsh and rocky, especially when the RCA contains higher amounts of RM (Snyder et al. 2018).

In general, there is no restriction of the amount of coarse RCA added in PCC for pavement applications. According to Appendix B, most experts agree that up to 100 percent virgin coarse aggregate can be replaced by coarse RCA in PCC. Pavement sections containing 100 percent coarse RCA have been successfully implemented in several projects (Choi and Won 2009; Gress et al. 2009; Roesler and Huntley 2009). From Appendix B, the safe level for RCA replacement depends on several variables such as the amount and quality of residual mortar attached to the particles, the type and quality of the natural aggregates used, mix-design adopted, and required properties of the RCA-PCC (Leandro Francisco Moretti Sanchez). Generally, fine RCA should be limited to 30 percent by the total volume of fine aggregate to avoid a harsh mix (Snyder et al. 2018). Interestingly, incorporation of adequate amount of fine RCA in the mixture could even lead to strength improvement (Gress et al. 2009) as a result of rehydration of the old cement in RM and improvements in the total aggregate gradation (Snyder et al. 2018).

Previous researchers invariably concluded that the RCA has higher absorption than virgin aggregate, and RCA might be more angular than virgin aggregate. Therefore, a 5–15 percent more water together with a use of water reducing admixture and/or fly ash is usually needed to maintain a good workability of RCA-PCC. Besides, a higher cementitious material content may be necessary to compensate strength reduction caused by the addition of RCA. A double mixing method might be effective in improving RCA-PCC strengths as well (Otsuki et al. 2003). In the double mixing method, water is divided into two stages and added separately. After fine and coarse aggregates (including RCA) are blended, the first portion of water is added. The rest of water is poured into the mixer after cement is added. Using this method, RCA is coated with a lower w/cm ratio than the rest of mortar matrix. Aggregates surrounded with less water tend to develop more compact ITZ.

Otsuki et al. (2003) stated that RCA plays a more dominating role in defining mixture strength for low w/cm ratio concrete. In the case of low w/cm, failure would start from old ITZ of RCA (Figure 6) because it is weaker than the new ITZ. For high w/cm, the new ITZ might be more vulnerable so the effect of RCA is less significant.

Researchers highly recommend preparing trial mixtures to confirm that the RCA-PCC mixtures will perform as intended.

Effect of RCA on PCC Properties

The properties of RCA can differ from virgin aggregate to some extent. By incorporating RCA, the properties of PCC can be altered depending on the quality of the RCA source. Based on the previously published documents on the use of RCA in PCC, the relevant findings on the changes of PCC properties due to incorporation of RCA are summarized in Table 3.

Table 3. Changes of RCA-PCC Properties due to Incorporation of RCA.

Property	Effect on property as the amount of RCA increases (in comparison w/ reference specimens made of virgin aggregate)	References	Mechanism
Slump	Increase	Katz (2003)	–
Slump	Reduction	Butler et al. (2011)	Note 1
Air content	Increase	Snyder et al. (2018)	Note 1
Abrasion resistance	Reduction	20 to 45% (Kosmatka et al. 2002)	Note 2
STS	Reduction	• 4% (Cheng 2005), 5% (Shi et al. 2010) w/ 25% coarse aggregate replacement (CAR) • 11% (Zhou et al. 2010) w/ 30% CAR • 7% (Cheng 2005), 15% (Shi et al. 2010), 21% (Zhou et al. 2010) w/ 50% CAR • 22% (Cheng 2005), 20% (Shi et al. 2010) w/ 75% CAR • 40% (Zhou et al. 2010) w/ 80% CAR • 10% (Cleary 2013; Ravindrarajah et al. 1987), 26% (Cheng 2005), 21% (Shi et al. 2010) w/ 100% CAR	Note 3
CS	Reduction	• 11 to 20% (Wainwright et al. 1993), 20 to 25% (Etxeberria et al. 2007) w/ 100% CAR • 21 to 38% (Wainwright et al. 1993) w/ 100% fine aggregate replacement (FAR)	Note 3
CS	No reduction	Optimal CAR - 30% (Bairagi et al. 1993; Desai 2004; Desai and Limbachiya 2006; Etxeberria et al. 2007; Limbachiya et al. 2000)	–
MOE	Reduction	• 22% (Kou et al. 2007) w/ 20% CAR • 2% (Etxeberria et al. 2007) w/ 25% CAR • 11% (Zhou et al. 2010), 40% (Xiao 2007) w/ 30% CAR • 10% (Etxeberria et al. 2007), 12% (Zhou et al. 2010), 30% (Kou et al. 2007), 41% (Xiao 2007)w/ 50% CAR • 41.5% (Xiao 2007) w/ 70% CAR • 12% (Etxeberria et al. 2007), 21% (Zhou et al. 2010), 32% (Kou et al. 2007), 43% (Xiao 2007) w/ 100% CAR	The excess mortar, attached to RCA, have lower elastic modulus than the aggregate itself.
Flexural strength	Reduction	• 11% (Cheng 2005) w/ 25% CAR • 2% (Hu 2007), 3% (Topcu and Şengel 2004), 12% (Cheng 2005) w/ 50% CAR • 2% (Hu 2007), 4% (Topcu and Şengel 2004) w/ 70% CAR • 13% (Cheng 2005) w/ 75% CAR • 6% (Hu 2007), 13% (Topcu and Şengel 2004), 14% (Cheng 2005) w/ 100% CAR	–
Flexural strength	No reduction	• (Hu 2007; Xiao and Li 2005)/ 30% CAR • (Xiao and Li 2005) w/ 50% CAR	–
Shear strength	Reduction	• 1% (Huang et al. 2010), 2% (Bai et al. 2010), 27% (Liu et al. 2010) w/ 30% CAR • 8% (Bai et al. 2010), 11% (Huang et al. 2010), 21% (Liu et al. 2010) w/ 50% CAR • 15% (Huang et al. 2010), 18% (Bai et al. 2010), 23% (Liu et al. 2010) w/ 70% CAR • 20% (Bai et al. 2010), 22% (Huang et al. 2010), 24% (Liu et al. 2010) w/ 100% CAR	–

Property	Effect on property as the amount of RCA increases (in comparison w/ reference specimens made of virgin aggregate)	References	Mechanism
Drying shrinkage	Increase	• 2.5 time (Gómez Soberón 2002; Gómez Soberón et al. 2001; Limbachiya et al. 2000) w/ 30% CAR • 1.25 time (Zhu and Wu 2010) w/ 50% CAR • 1.05 time (Guo et al. 2011; Zhang et al. 2009)/ 70% CAR • 1.58 time (Zhu and Wu 2010), 1.1 time (Guo et al. 2011; Zhang et al. 2009) w/ 100% CAR	Due to high absorption of RCA
Creep	Increase	• 30% (Domingo-Cabo et al. 2009) w/ 20% CAR • 50% (Zou et al. 2009) w/ 30% CAR • 40% (Domingo-Cabo et al. 2009) w/ 50% CAR • 60% w/ 65% CAR • 51% (Domingo-Cabo et al. 2009), 110% (Zou et al. 2009), 10% (Ye 2009) w/ 100% CAR	–
Thermal expansion	Increase	0 to 30% (ACPA 2009).	–
Thermal expansion	Reduction	40% (Smith and Tighe 2009) w/ 100% CAR	–
Carbonation resistance	Reduction	• 57% (Yuan et al. 2010) w/ 25% CAR • 2% (Lei and Xiao 2008; Zhang and Yan 2009) w/ 30% CAR • 60% (Yuan et al. 2010), 40% (Zhang and Yan 2009), 31% (Lei and Xiao 2008) w/ 50% CAR • 53% (Zhang and Yan 2009), 44% (Lei and Xiao 2008) w/ 70% CAR • 62% (Yuan et al. 2010), w/ 75% CAR • 25% (Zhang and Yan 2009), 18% (Lei and Xiao 2008) w/ 100% CAR	Influenced by the RCA content, RCA quality and curing age
Chloride penetration	Increase	• 5% (Zhang et al. 2009) w/ 30% CAR • 10% (Zhang et al. 2009)w/ 70% CAR • 35% (Du et al. 2006), 7% (Zhang et al. 2009), 3% (Hu et al. 2009) w/ 100% CAR	Note 1
ASR	May or may not increase of ASR	Shayan and Xu (2003)	Depend on RCA source and the alkali levels of the original concrete

– No data

- RCA may be contaminated with chloride ions from the application of deicing salts to roadway surfaces or with sulfates from contact with sulfate-rich soils. Chloride ions are associated with corrosion of steel, while sulfate reactions lead to expansive disintegration of cement paste.
- The performance of concrete made with RCA can also be improved by the addition of supplementary cementitious admixtures. Fly ash, a by-product of the coal industry, is the most commonly used pozzolan in civil engineering structures. When introduced to concrete, fly ash extends the hydration process, allowing a greater strength development and reduced porosity.

Note 1: RCA applied in recycled aggregate concrete (RAC) possesses two types of ITZ, one between the RCA and new mortar matrix and the other between RCA and old mortar attached (old ITZ) (Figure 6). The old mortar portions of the RCA are in general porous in nature and contains fine micro-cracks can behave as weak areas in RAC. The pores and micro-cracks in the old mortar portions increase water absorption, which causes availability of less water for hydration at the ITZ regions of RCA. The mortar filled with pores and air voids adds additional volume to the aggregate with very little additional weight, resulting in lower specific gravities.

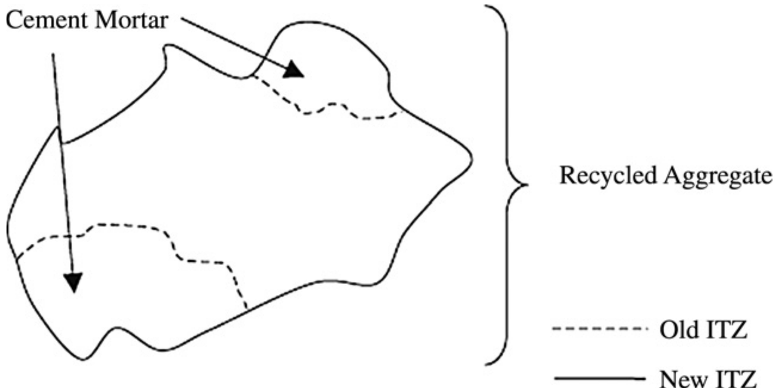


Figure 6. ITZ of RAC Constructed with RCA (Xiao et al. 2012).

Note 2: The soft mortar attached to the RCA and the presence of partially fractured particles due to improper or uneven crushing may be the main reason of reduction in abrasion resistance. Old mortar is by nature weaker than the aggregates themselves making it more likely to be abraded from the aggregate.

Note 3: Due to the weaker composition and increased number of bonded interfaces of RCA, tensile strengths are typically lower in RAC than in conventional PCC. The higher air content that results from the increased number of bonded interfaces of RCA has also been found to decrease the CS of RAC.

Effect of RCA on PCCP Performance

The current practice is to dominantly use RCA as a base material. However, putting RCA in pavement base might introduce leaching problems, so bounding RCA in concrete can be more environmentally friendly. This section discusses the potential impacts that the changed concrete properties due to RCA addition can bring to pavement performance and some precautionary measurements to promote the use of RCA in PCCP.

Coefficient of Thermal Expansion

Concrete made of RCA typically show a higher CoTE. The higher CoTE generates higher curling stresses and causes more distresses in pavement slabs. A short joint spacing is recommended to compensate the negative effects caused by the higher CoTE.

Modulus of Elasticity

Due to the presence of RM, RCA has lower MOE compared to its original aggregate. Researchers' previous simulation work (Shi 2018) indicates that PCC slab with reduced MOE would induce higher DE to the base support, causing higher slab faulting and base erosion. Therefore, building a strong base and subgrade support is highly recommended for RCA-PCCP. On the other hand, the reduced MOE is beneficial to reduce transverse cracking width for CRCP (Shi et al. 2018b).

Shrinkage

RCA concrete often exhibits higher shrinkage (Obla et al. 2007), which can cause pavement to crack prematurely. A few field sections showed an excessive amount of longitudinal cracking in CRCP, which were believed to be associated with higher shrinkage

(Roesler and Huntley 2009). Because of higher shrinkage, RCA concrete pavement may not be placed in hot summer. According to Appendix B, the drying shrinkage became unacceptably high when incorporating fine RCA replacement levels above 30 percent (David Lange).

Aggregate Interlock

RCA may have worse aggregate interlock due to smaller aggregate size and abrasion during the RCA production. Lower aggregate interlock yields reduced LTE, and consequently, leads to more pavement distresses. Dowel bars are usually recommended for pavement built with RCA concrete.

Corrosion

The higher amount of chemicals (i.e., chloride from deicing salt) and the higher porosity of RCA may cause steel to corrode faster than normal. Washing RCA might be needed to remove the chemicals. According to Appendix B, using RCA in reinforced concrete pavement might be only allowed in warmer regions where deicing salts are not used (Richard Meininger). Some states such as Virginia do not allow RCA in reinforced concrete pavement. The use of epoxy-coated steel or other corrosion resistant steels may be helpful. Besides, the presence of chemicals can also accelerate RCA concrete setting, so water retarder is usually used.

Bond Strength between RCA Concrete and Steel

When coarse RCA is used alone, the bond is reported to be good (Reza and Wilde 2017). Fine RCA can introduce more bonding problems, so it should be limited.

Life Cycle Assessment for Use of RCA in PCCP

Donalson et al. (2011) provided a sustainable assessment of RCA used in highway base construction. In their study, the use of RCA not only generates social and environmental benefits but also offers economic benefits provided the hauling distance of RCA is negligible compared to that for virgin aggregate. They further mentioned that it is possible that the use of RCA could become the only viable option for pavement construction in the future due to gradual reduction of natural aggregate resources. Mroueh et al. (2001) conducted a life cycle assessment of pavements focusing on the use of industrial by-products, which included the use of RCA as base materials. They created an index to represent the weighted loadings on the environment. They found that the pavements built with RCA base could have less negative effect on the environment compared to the pavement built with natural material. In all the compared cases, one of the crushed concrete constructions achieved the greatest environmental benefits due to lower use of energy and emissions of NOx, SO_2, CO_2, and volatile organic compounds.

Ram et al. (2011) conducted an extensive life cycle assessment for a selected number of Michigan DOT concrete pavement sections to evaluate the sustainable benefits of using recycled and industrial by-product materials in concrete pavements. They concluded that incorporating coarse RCA in paving concrete could yield comparable pavement performance when the traffic level is low, compared to pavement built with natural coarse aggregates. At higher traffic levels, the pavements built with RCA exhibited poor performances so that most of them underwent complete reconstruction or overlaid with JPCP at about 20 years. The existing RCA pavements in Michigan were all built in 1980s, and most of them were jointed reinforced concrete pavements. The failure of RCA pavements was likely due to some combination of small top size aggregate, poor aggregate interlock, long joint spacing, and too little reinforcement. These defects can be overcome via a better material selection and structure design. Ram et al. (2011) found that the use of RCA could lead to significant positive environmental benefits. The environmental benefits can be further maximized by using on-site recycling instead of regional recycling, which reduces pollution due to transportation.

Reza and Wilde (2017) did a comprehensive life cycle cost analysis on using RCA in PCCP covering different hypothetical pavement construction scenarios. A total of eight alternatives were considered. The different scenarios have varying RCA replacement level, w/cm, slab thickness, and pavement service life to the first major concrete pavement rehabilitation. Table 4 summarizes the pavement scenarios.

Table 4. Different Pavement Scenarios for the Life Cycle Cost Analysis by Reza and Wilde (2017).

Scenarios	%RCA	w/cm	Slab thickness (in.)	Analysis life period (year)
1	0	0.37	9.0	59
2	50	0.37	9.0	50
3	50	0.37	10.1	59
4	50	0.36	9.0	59
5	100	0.37	9.0	46
6	100	0.37	11.2	59
7	100	0.35	9.0	59
8	50	0.39	6-in. RCA-PCC as lower lift, 3-in. exposed aggregate concrete as upper lift	59

The life cycle cost analyses indicate that using RCA in new concrete pavement construction can be very economical due to avoiding the high cost of purchasing and hauling natural aggregate for concrete, despite the fact that RCA-PCCP requires a higher expense for sawcuts and dowel bars, and two-lift pavement requires a higher construction cost. The saving in cost can be maximized when RCA is used in concrete slab compared to using RCA in the pavement base layer. Although addition of RCA yields detrimental effects on concrete properties, either changing the pavement structural design (e.g., increase concrete slab thickness) or strengthening the mix (e.g., increase the cementitious material and decrease the w/cm) can make RCA-PCCP have similar performance with plain concrete pavement. The life cycle cost analysis showed that strengthening the mix is more cost effective than increasing pavement thickness.

Reza and Wilde (2017) also did life cycle analyses to compare alternative 7 against alternative 1 with the PaLATE tool. They concluded that in many cases the RCA-PCC case appeared to have higher environmental benefit.

Verian et al. (2013) conducted a cost-benefit analysis of using RCA in new concrete pavements. In their study, a hypothetical 3-lane mile-long pavement built with 50 percent of coarse RCA in the concrete layer and 100 percent coarse RCA in the base layer was evaluated. Combining the cost savings due to natural aggregate replacement and landfilling the old concrete pavement, around $3 million saving could be realized.

Recently, researchers published a paper focusing on sustainability assessment for PCC containing RAP aggregates (Shi et al. 2018a). In this paper, the economic, social, and environmental impacts of concrete pavement made with RAP aggregates were extensively studied via an economic input-output life cycle assessment (EIO-LCA) approach. The results showed that the single-lift RAP-PCCP could yield the highest economic benefits, while the two-lift construction could have highest positive impacts from social and environmental perspective. Since RCA-PCC is analogical to RAP-PCC (both contained recycled aggregates, and both have reduced strength and modulus and higher CoTE), it is expected that RCA-PCCPs could yield sustainable benefits as well.

To evaluate potential sustainable benefits of using RCA in PCC, a life cycle assessment to compare an RCA-PCCP and a plain PCCP covering all three aspects of sustainability, namely the economic impact, social impact, and environmental impact was performed in this study using an EIO-LCA approach. The EIO-LCA theory was proposed by the Nobel Prize winner Wassily Leontief and was further developed by the Green Design Institute at Carnegie Mellon University. The EIO-LCA approach has been widely used in various research areas, which includes the field of pavement sustainability (Mukhopadhyay and Shi 2017; Rew et al. 2018; Shi et al. 2018a). In this life cycle assessment, the output flows for life cycle inventory during the materials production and construction, use, and end-of-life phases were obtained and then assessed with the TRACI for both RCA-PCCP and plain PCCP cases. Details of the life cycle assessment is documented in Appendix C. The major findings from this life cycle assessment case study are:

- The output flows result during the materials production and construction indicates that the RCA-PCCP yields significantly less economic, environmental, and social burden compared to the plain PCCP. The sustainability of the RCA-PCCP during the materials production and pavement construction is attributed to less consumption of virgin aggregate, less virgin aggregate transported to the ready-mix plant, and less concrete debris transported to and deposited in the landfill site.
- The RCA-PCCP was slightly less sustainable compared to the plain PCCP during the use phase. The rougher pavement surface of the RCA-PCCP causes higher tire and fuel consumption for vehicles, which poses higher negative impacts to the economy, environment, and society.
- The results of the total output flows and the characterization factors in the TRACI for the entire pavement life cycle are mixed. Although the benefits of using RCA in the materials production and construction phase are obvious, the higher amount of negative impacts during the use phase is more dominating in the entire life cycle. As a result, it cancels

out the benefits achieved during the materials production and construction for the RCA-PCCP to some extent. But still, use of RCA to reconstruct concrete pavement could have fewer negative impacts on the characterization factors including Human Health Particulate air, Smog air, Ecotoxicity (low), Ecotoxicity (high), Human Health Cancer (high), and Human Health NonCancer (high) compared to building concrete pavement using virgin aggregates.

In conclusion, use of RCA in PCCP could potentially yield benefits in some of the sustainable categories. These benefits will only be magnified with a growing level of environmental awareness and further diminishment of local virgin aggregate sources in the future. Additionally, a modest $2/ton landfill cost was used to represent the cost in the Midwestern region of the United States. It also accounts for a bulk discount for the size of this project (Verian et al. 2013). The landfill costs could be significantly higher than this value nationwide. According to Bogert and Morris (1993), National Solid Wastes Management Association reports that tipping fees increased from an average of $8/ton in 1985 to $34.29/ton in 2004, with averages as high as $70.53/ton in the Northeast region.

OBJECTIVE 2: PERFORMANCE EVALUATIONS OF THE EXISTING RCA PAVEMENTS IN OKLAHOMA

During the 1980s, ODOT constructed several sections of PCCP that contained RCA replacing virgin coarse aggregate up to 100 percent. These existing sections now offer a unique opportunity to evaluate the long-term performance of RCA concrete pavement. With the increasing demand of pursuing sustainable construction using recycled materials, the use of RCA in concrete potentially offers the benefits of reducing cost and decreasing carbon footprint without compromising performance and service life if precaution measures are taken. The main purpose of this objective was to carry out a long-term performance evaluation of selected RCA pavements existing in Oklahoma through a detailed field evaluation followed by laboratory studies of the core specimens. The major tasks in this objective included use of FWD testing to assess pavement structural performances, laboratory determination of mechanical properties, and concrete microstructural analysis with a specific emphasis on understanding the nature of crack propagation using the petrographic technique.

Section Description

A detailed review of existing documents was performed for two selected RCA-PCCPs near Oklahoma City:

1. A portion of I-40 JPCP in Oklahoma County between mileposts 165 and 173, constructed in 1983.
2. A portion of I-35 CRCP in Logan County between mileposts 147 and 152, constructed in 1989.

I-40 Pavement

Most of the information on the I-40 RCA-PCC project came from a Transportation Research Board paper titled *Recycling PCC Roadways in Oklahoma* (Hankins and Borg 1984). The original pavement was constructed in 1961, which had more than 20 years' service life before it was recycled. Each direction of the pavement had a 4-ft inside shoulder, two 12-ft lanes, and a 10-ft outside shoulder. The original 9-in. PCC slab contained limestone aggregates with a maximum nominal size of 1.5 in. and 15-ft contraction joints sealed with conventional asphaltic material. The shoulders and PCC were both built on a 6 in. soil asphalt base, which in turn rested on 5 in. of selected material.

The original pavement was found to have undergone moderate D-cracking near the transverse joints. Two rehabilitation approaches were proposed back in that time: one was conceived as a breaking and seating of the exiting PCCP followed by overlaying with asphalt concrete. The other one was to remove the exiting PCCP and replace it with a 10-in. PCC layer with RCAs produced from the original slabs. The motivation of using RCA for this project was that the nearest virgin aggregate source was a quarry more than 50 miles away. Replacing virgin aggregate with RCA avoided purchasing and delivering 63,000 tons of natural aggregate, which saved $0.8 million. This PCC recycling project was $0.7 million cheaper than the alternative rehabilitation plan with an asphalt concrete overlay, so the PCC recycling approach was the best bid option.

The reconstruction of the 7.75-mile long I-40 section started on March 10, 1983. The existing pavement was first removed and delivered to a standard Cedar Rapids crusher plant that used hammer mills. Small quantities of steel rebar were removed by suspending a magnet over the conveyor, while the wire cages holding dowel bars were skillfully extracted by the loader operator. The plant was able to convert 42 percent of broken pavement into coarse RCA. Using the hammer mills produced more fine materials than expected. Table 5 lists the gradations of fractionated RCA materials. The coarse RCA met the coarse aggregate size requirements. Because the original pavement showed moderate D-cracking, the maximum aggregate size of RCA was reduced to 0.75 in. to minimize the potential for D-cracking in the new project. Due to a lower efficiency in producing RCA, an additional 4,871 tons of virgin aggregate were needed to finish the paving, which resulted in a portion of the paved section containing 100 percent virgin coarse aggregates.

Table 5. Gradation of RCA for I-40.

Sieve size	Coarse RCA	Fine RCA
1 in.	100	–
¾ in.	98.5	–
½ in.	46.5	100
3/8 in.	11.2	99.2
No.4	1.5	74.8
No.10	–	48.5
No.40	–	19.4
No.80	–	9.2
No.200	–	4.5

– No data

During the removal of the exiting pavement, the soil asphalt was consolidated by the paving-crushing hammer. To restore the grade and eliminate the need to mill the shoulders, an average of 3.5 in. of soil asphalt was added and re-blended with the existing soil asphalt base for the first section. For the remaining three sections, the contractor combined the RCA fines with existing 6 in. soil asphalt instead of blending additional soil asphalt in the base. This approach provided the necessary profile and base strength.

Table 6 shows the mix design of the I-40 rehabilitation project (Hankins and Borg 1984). The averaged 7-day CS of five specimens determined in the lab was 3856 psi for control PCC and was 3618 psi for RCA-PCC. Field RCA-PCC samples had 1.5–2.0 in. slump, 4.6 percent air content, and 3160–4580 psi 7-day CS, which satisfied Class A concrete requirements. The placed concrete was tined transversely to enhance skid resistance. Curing compound was applied on the concrete to facilitate curing. This project was opened to traffic in early Nov. 1983, after 247 calendar days of work.

Table 6. Mix Design for I-40 (Hankins and Borg 1984).

Materials	RCA PCC	Control PCC
Portland cement (lb/cy)	479	479
Fly ash (lb/cy)	115	115
Natural sand (lb/cy)	1130	1206
Coarse aggregate* (lb/cy)	1695	1864
Water (gal/cy)	30	30
Density (lb/cf)	136	145
Entrained air (%)	5	5

* For RCA-PCC, the coarse aggregate was 100% coarse RCA; for control PCC, the coarse aggregate was 100% virgin limestone.

I-35 Pavement

Despite efforts were made collecting related document for I-35 RCA project, little information in the literature was available. The only reference identified is the National Cooperative Highway Research Program (NCHRP) 154 project report (Yrjanson 1989), which states:

> *In April 1988, the Oklahoma DOT awarded a contract to reconstruct a 5.77-mile section of I-35 north of Edmond. The original dowel-mesh pavement with soil-cement shoulders was constructed in 1960. The contractor planned to recycle this pavement into a new 10-in. CRCP with PCC shoulders. The use of epoxy-coated steel was recommended for the CRCP. Installation of a drainage system during construction was also recommended.*

Based on the feedback received from the original contractor, the southbound lanes between mileposts 147 and 152 on I-35 of a CRC pavement were constructed using RCA (100 percent replacement of coarse virgin aggregate) using epoxy coated steel. The northbound lanes between the same mileposts were constructed using virgin limestone and black steel for the CRCP.

Field Investigation

Researchers performed a field observation and testing for the I-35 and I-40 pavement sections from May 30, 2017, through June 2, 2017. A pavement distress survey was conducted to determine the best testing locations on each pavement. Based on the survey observation, an elaborate plan of FWD testing and sample coring was established. The field survey (Figure 7) along with the petrographic examination of the field cores (presented later) revealed that the control sections in I-40 are located between mile post 165 and 168, while the remaining portion of the section is RCA-PCCP. The completed FWD testing and sample coring work is presented in Table 7 with details summarized as below.

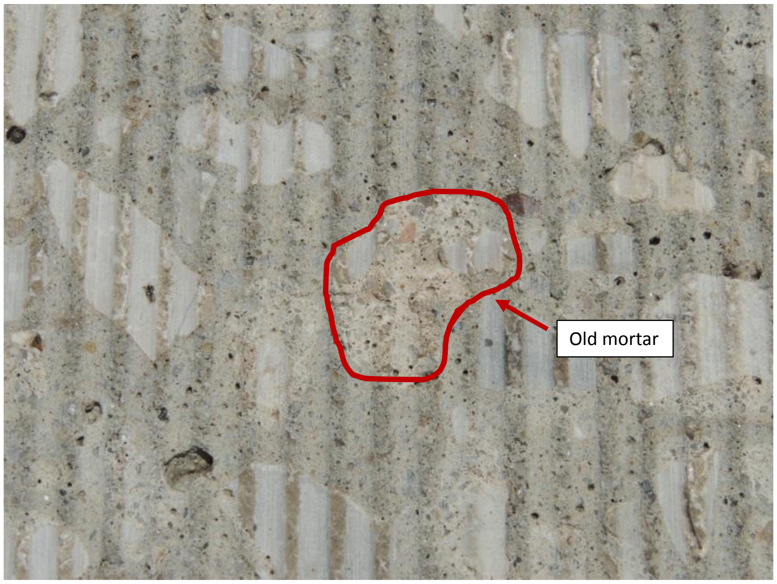


Figure 7. Identification of RCA with Old Mortar from the Field Survey in I-40 EB Segment 3.

Table 7. FWD Test and Sample Coring for I-40 and I-35.

Date	Pavement	Segment location for FWD testing	Approximate GPS location	PCC type	Number of cores
May 31, 2017	I-40 EB, JPCP	Segment 1: near milepost 167.5 (CON-1)	(35.384477, -97.24055)	Control	4 PCC+1 base
May 31, 2017	I-40 EB, JPCP	Segment 2: between milepost 167 and 168 (close to 168) (CON-2)	(35.384475, -97.236373)	Control	4 PCC+1 base
May 31, 2017	I-40 EB, JPCP	Segment 3: between milepost 168 and 169 (1/4 mile away from 169 miles westwards) (RCA)	(35.384423, -97.220154)	RCA	4 PCC+1 base
May 31, 2017	I-40 EB, JPCP	Segment 4: near milepost 167.5 (See note 1) (CON-1-T)	(35.384477, -97.24055)	Control	No cores
May 31, 2017	I-40 EB, JPCP	Segment 5: exactly on milepost 169 (FWD has not been performed)	Not recorded	RCA	1 PCC
June 1, 2017	I-35 SB, CRCP	Segment 1: between milepost 149 and 148, staring from marking 1244 (RCA-1)	(35.763901, -97.416022)	RCA	4 PCC + 1 base
June 1, 2017	I-35 SB, CRCP	Segment 2: near 148, starting from marking 1208 (RCA-2)	Not recording	RCA	No cores
June 1, 2017	I-35 SB, CRCP	Segment 3: near marking 1235 (FWD has not been performed)	(35.766026, -97.415973)	RCA	4 PCC+ 1 base
June 2, 2017	I-35 NB, CRCP	Segment 1: ending at marking 1203 (CON)	Not recorded	Control	5 PCC+1 base (base is attached)
June 2, 2017	I-35 NB, CRCP	Segment 2: (FWD has not been performed)	Not recorded	Control	4 PCC+1 base

Note 1: Same segment location with segment 1. The FWD test was performed in afternoon to account for the effect of pavement temperature. EB = eastbound; SB = southbound; NB = northbound.

I-40 EB JPCP (the RCA and Control Sections)

Due to bad conditions of the truck lane, the FWD testing was focused on the passing lane between milepost 167.5 and 169. The inside lane showed less distress and less patching, which better represented the original pavement. Working on the inside lanes allowed less interference with the on and off ramp traffic. It was anticipated that both RCA and control sections would be encountered within these segments based on the field observation. Five segments (Table 7) were selected, and the FWD testing was performed on four of them. To evaluate the effect of pavement temperature on FWD results, FWD testing was repeated in the afternoon on the same locations of Segment 1 (the segment was relabeled as Segment 4). The first FWD test of Segment 1 was performed between 10:07 a.m. and 11:13 a.m. on May 31, 2017, and the pavement surface temperature was recorded as 84°F; the second FWD test of Segment 1 was conducted from 2:27 p.m. to 3:15 p.m. with the pavement surface temperature of 97°F. For each of the FWD segments, three adjacent PCC slabs were tested at interior, edge, and corner locations (Figure 8). Each slab was 12 ft in width and 15 ft in length, which matched with the information from the literature.

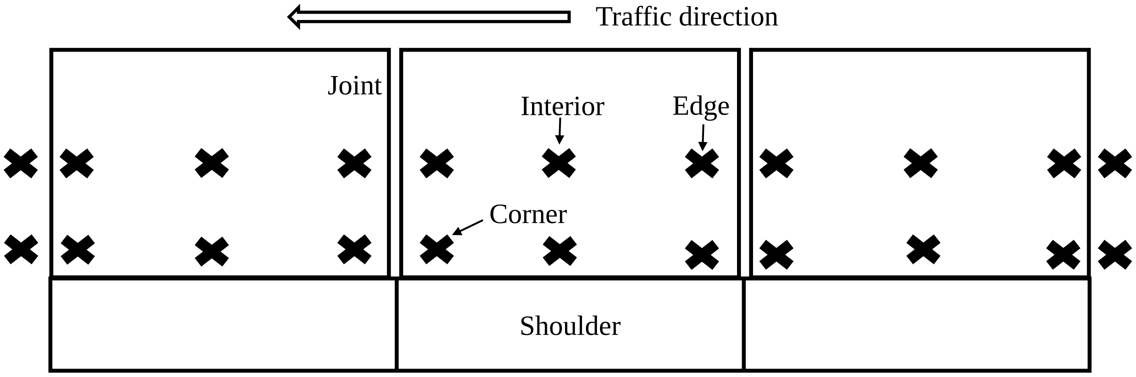


Figure 8. Sketch of FWD Loading Position for I-40.

In total, 16 cores were collected from segments 1, 2, 3, and 5. For Segment 1, a 6-in. diameter core was taken all the way through the slab and the base layer. A 4-in. diameter PCC core was obtained from the second slab and another two 6-in. PCC cores were taken from the third slab. For both segment 2 and 3, a 6-in. diameter PCC slab core with base sample, two 4-in. diameter PCC cores and one 4-in. diameter were taken from the first, second, and third slab, respectively. Only one 6-in. PCC slab core was obtained from Segment 5 to confirm the material identification through petrographic examination. The base material is something similar to soil (Figure 9). The interface between the base and PCC slab appeared to be weak as such all the PCC cores were debonded from the base samples (Figure 10). Shortly after the base samples were extracted, they started to develop cracks due to drying. During the test, a pavement distress map for the testing spots was recorded. A significant number of longitudinal cracks were found during the observation of the entire pavement section (Figure 11), but the severity of the distress is less in the passing lane. The observable D-cracking was not found in I-40 pavement. This suggests that the D-cracking preventive measure of using smaller aggregate size appeared to be working in the field.

Figure 9. Picture of a Base Core for I-40.

Figure 10. Picture of De-bonding.

Note, relatively weak top surface of the base is manifested.

Figure 11. Picture of Longitudinal Cracking on I-40.

I-35 CRCP

RCA Section on the SB

The traffic control for I-35 SB was set up between mileposts 150 and 148. Two pavement segments between mileposts 149 and 148 were subjected to FWD testing on the truck lane. A large amount of effort was spent on testing Segment 1, which contained 120 ft of pavement. The cracking pattern together with pavement distresses was carefully mapped. A limited amount of FWD data was recorded in Segment 2 due to the time limitations. Segment 2 contained approximately 40 ft of pavement. For each segment, FWD loadings were applied both in the middle of the slab and in the edge of the slab on the approach and leave sides of the transverse cracking. A limited amount testing was also carried out in the middle of selected cracked panels (Figure 12).

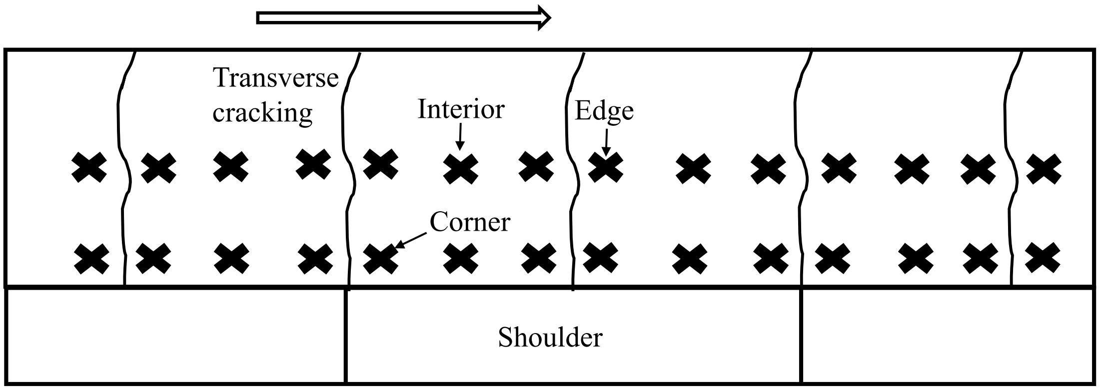


Figure 12. Sketch of FWD Loading Position for I-35 (both SB and NB).

In total, 10 cores were taken from Segment 1 and Segment 3. For each segment, a 6-in. diameter PCC core with base material and three 4-in. PCC cores were taken. The core locations were selected to ensure the cores were free of cracks. A metal detector was used to avoid the rebar, but still a few core samples contained some portion of reinforcement. An additional PCC core was taken from a punch out distress location in Segment 1. The base material was identified as asphalt concrete (Figure 13). It was much stronger than the base of I-40 pavement. However, researchers were unable to obtain a completely attached PCC and base sample from the I-35 SB pavement section.

Figure 13. Picture of a Base Core for I-35 SB.

Other than the FWD testing, researchers performed additional field surveys on the I-35 SB sections. The entire one mile of pavement section of I-35 SB truck lane (milepost 150 to milepost 149) was carefully examined. Twelve punchouts and 5 patches were found within this pavement section (Figure 14). Researchers also found that almost 100 percent of the shoulder joints coincided with transverse cracks in the PCC slab (Figure 15). A survey of 98 shoulder joints indicated that 70.4 percent of the associated transverse cracks were wide cracks. Researchers believe that such shoulder joint associated transverse cracks were related to the tie bars in the PCC. The steel was epoxy treated, which might result in a weaker bond between the concrete and steel reinforcement.

Figure 14. Picture of a Typical Punchout from I-35 SB.

Figure 15. Picture of a Shoulder Joint Coincided with a Transverse Crack from I-35 SB.

Control Section on the NB

The pavement section between milepost 149 and 151 was FWD tested and cored. Only one segment (Segment 1) covering 180 ft of truck lane was subjected to FWD testing. Similarly, the loadings were positioned in the middle and on the edge of the slab, as well as in the middle of a panel away from cracks (Figure 12).

In total, 10 samples were cored from Segment 1 and Segment 2. Same with the I-35 SB, one fourth of the coring reached the bottom of the base. Interestingly, the base portion in the sample from Segment 1 was fully attached to the PCC portion of that sample (Figure 16), indicating a good bonding in the interface of the two materials. The core with base sample from Segment 2 was detached though.

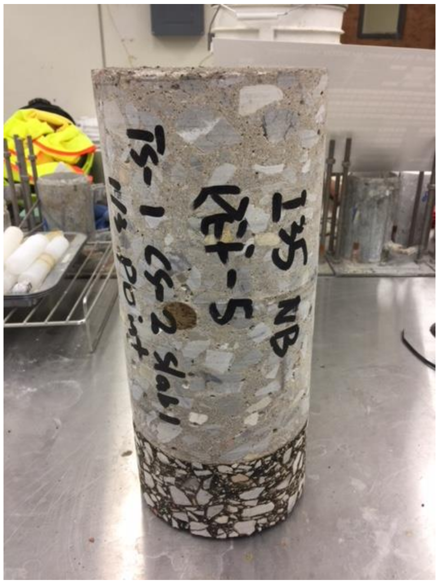


Figure 16. Picture of an Attached Base Core from I-35 NB.

Different from the I-35 SB, the NB pavement section had significantly less amount of shoulder joint associated transverse cracking. The overall pavement condition appeared to be better than that for the SB lanes.

The average transverse crack spacing for both SB and NB was calculated based on the distress maps. The RCA section showed significantly shorter mean crack spacing (2.6 ft) compared to the control section (5.2 ft). The shorter crack spacing is attributed to a combined effect of increased shrinkage and CoTE and reduced aggregate bond strength for the RCA concrete (Roesler and Huntley 2009). Slabs with shorter crack spacing tends to develop more punchout if the base support is lost (Zollinger et al. 1999).

The core samples were carefully labeled, wrapped, transported, stored, and documented in the lab. Table 8 summarizes information on the core samples with different testing purpose.

Table 8. Summary of Core Sample Information.

Location	Sample ID	Sample Diameter (in.)	Sample thickness (in.)	Material	Test purpose
I-40 EB, Segment 1	I40-1-1	6	9.7	Control-PCC	PS
I-40 EB, Segment 1	I40-1-2	6	9.4	Soil asphalt	OB
I-40 EB, Segment 1	I40-1-3	4	9.4	Control-PCC	CS
I-40 EB, Segment 1	I40-1-4	6	9.8	Control-PCC	MOE
I-40 EB, Segment 1	I40-1-5	6	9.8	Control-PCC	STS
I-40 EB, Segment 2	I40-2-1	6	10.1	Control-PCC	PS
I-40 EB, Segment 2	I40-2-2	6	9.8	Soil asphalt	OB
I-40 EB, Segment 2	I40-2-3	4	9.8	Control-PCC	CS
I-40 EB, Segment 2	I40-2-4	4	9.75	Control-PCC	MOE
I-40 EB, Segment 2	I40-2-5	4	9.5	Control-PCC	STS
I-40 EB, Segment 3	I40-3-1	6	9.9	RCA-PCC	PS
I-40 EB, Segment 3	I40-3-2	6	9.7	Soil asphalt	OB
I-40 EB, Segment 3	I40-3-3	4	9.8	RCA-PCC	CS
I-40 EB, Segment 3	I40-3-4	4	9.25	RCA-PCC	MOE
I-40 EB, Segment 3	I40-3-5	4	9.2	RCA-PCC	STS
I-40 EB, Segment 5	I40-5-1	6	9.8	RCA-PCC	PS
I-35 SB, Segment 1	I35SB-1-1	6	10.2	RCA-PCC	PS
I-35 SB, Segment 1	I35SB-1-2	6	3.5	Asphalt concrete	OB
I-35 SB, Segment 1	I35SB-1-3	4	10.1	RCA-PCC	CS
I-35 SB, Segment 1	I35SB-1-4	4	9.8	RCA-PCC	MOE
I-35 SB, Segment 1	I35SB-1-5	4	9.5	RCA-PCC	STS
I-35 SB, Segment 3	I35SB-3-1	6	10.7	RCA-PCC	PS
I-35 SB, Segment 3	I35SB-3-2	6	3.3	Asphalt concrete	OB
I-35 SB, Segment 3	I35SB-3-3	4	10	RCA-PCC	CS
I-35 SB, Segment 3	I35SB-3-4	4	9.75	RCA-PCC	MOE
I-35 SB, Segment 3	I35SB-3-5	4	9.6	RCA-PCC	STS
I-35 NB, Segment 1	I35NB-1-1	6	10.1+3.3	Control PCC+ Asphalt concrete	OB
I-35 NB, Segment 1	I35NB-1-2	4	10.1	Control PCC	CS
I-35 NB, Segment 1	I35NB-1-3	4	10.4	Control PCC	MOE
I-35 NB, Segment 1	I35NB-1-4	4	10.2	Control PCC	STS
I-35 NB, Segment 1	I35NB-1-5	6	10.1	Control PCC	PS
I-35 NB, Segment 2	I35NB-2-1	6	10.1	Control PCC	PS
I-35 NB, Segment 2	I35NB-2-2	6	3.1	Asphalt concrete	OB
I-35 NB, Segment 2	I35NB-2-3	4	9.6	Control PCC	CS
I-35 NB, Segment 2	I35NB-2-4	4	9.5	Control PCC	MOE
I-35 NB, Segment 2	I35NB-2-5	4	10	Control PCC	STS

PS-petrographic study: microstructure of the sample has been studied through thin section observation under a transmitted light optical microscope.
CS-compressive strength: compressive strength of the sample was tested according to ASTM C39.
MOE-modulus of elasticity: modulus of elasticity of the sample was tested according to ASTM C469.
STS-splitting tensile strength: splitting tensile strength of the sample was tested according to ASTM C496.
OB-visual observation.

Lab Test and FWD Data Analysis

Petrographic Examination

The core specimens from each location were cut vertically followed by selecting one sample (a slice of 70 × 85 mm) from the top and one from the bottom to make thin sections (~25 µm thick) of 55 × 75 mm dimension. The following observations are based on examination of these thin sections (Figure 17) under a transmitted light optical microscope. A blue dye was used during thin section preparation to highlight air voids, cracks, pores, and others open spaces in the studied concrete samples. Air voids, cracks, and pores are highlighted by the blue color of the dye used in all the images provided.

Figure 17. Thin Section Observation under a Transmitted Light Optical Microscope.

The presence of RCA particles was observed in thin sections (Figure 18–Figure 20) prepared using core samples from the I-40 RCA sections (i.e., Segments 3 and 4).

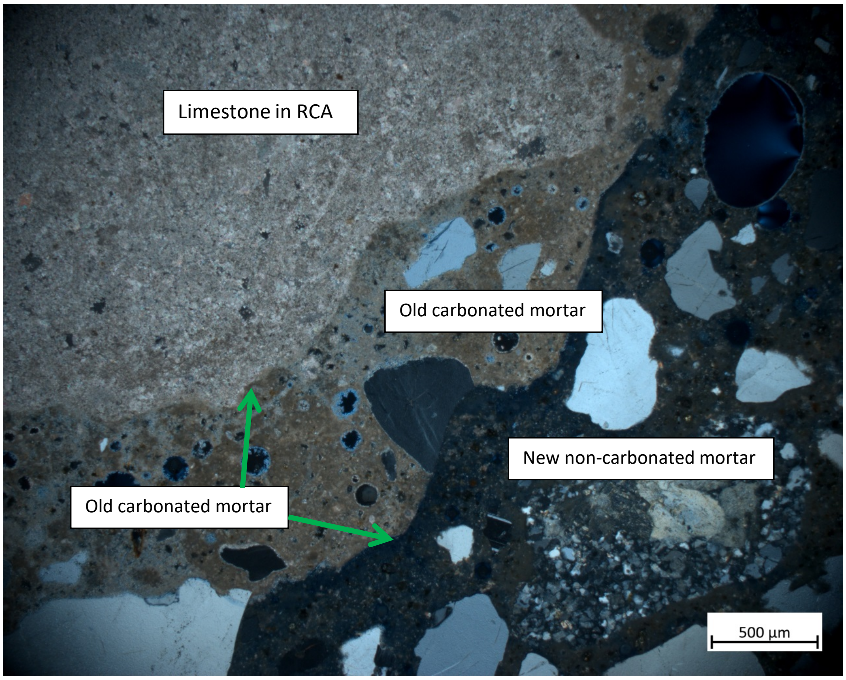


Figure 18. Carbonated Old Mortar Is Adhered with the Limestone Particle, Cross Polarized Light (XPL), RCA Sample from Segment 4.

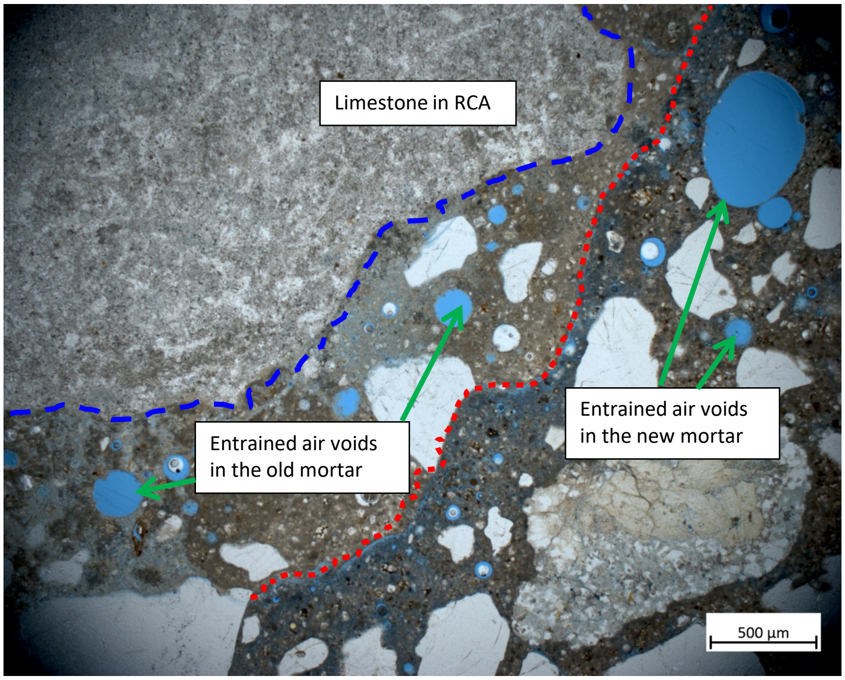


Figure 19. Plane Polarize (PPL) View of Figure 18.

The presence of entrained air voids within the old carbonated mortar is visible.

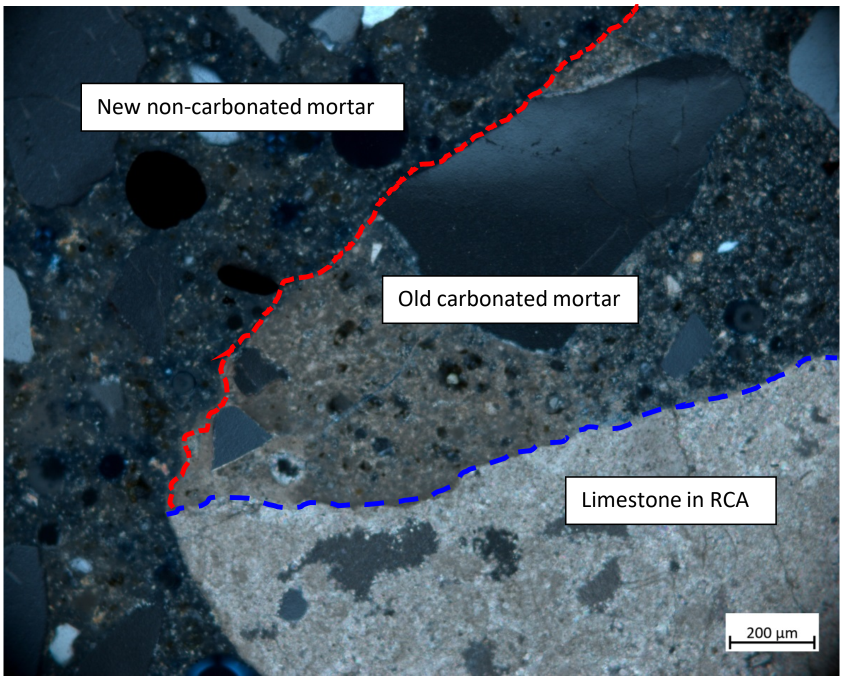


Figure 20. Presence of Old Carbonated Mortar Attached with the Limestone Particle in RCA, Core Sample from Segment 3, XPL.

The presence of RCA particles was also evident in thin sections (Figure 21) prepared using core samples from the I-35 RCA sections (i.e., Segments 1 and 3).

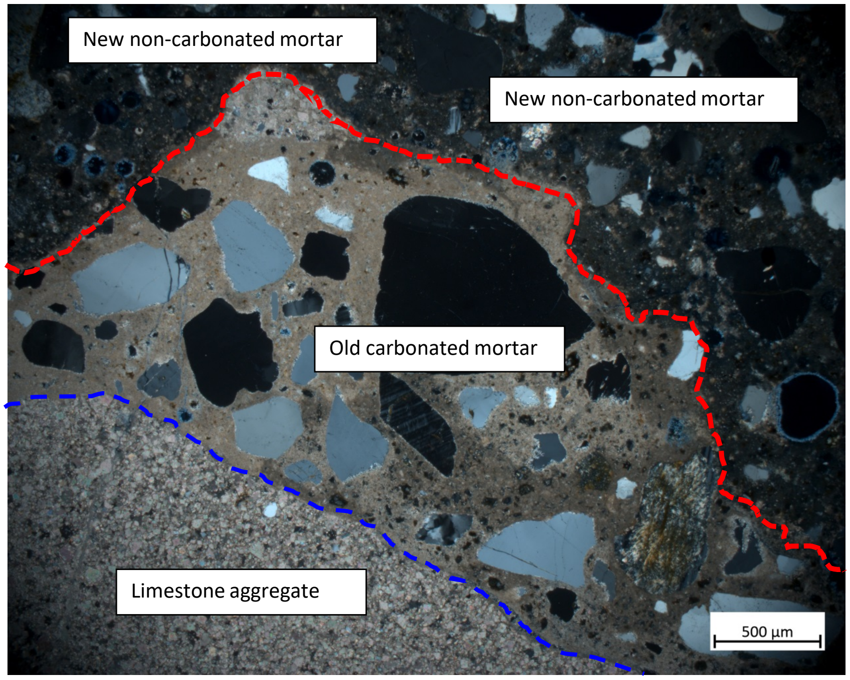


Figure 21. Presence of Old Carbonated Mortar Attached with the Limestone Aggregate in the RCA Sample from Segment 1, XPL.

To see the nature of crack propagation in the RCA-PCC, the thin sections were prepared using some selected cracked specimens after the splitting tensile test followed by observations under the transmitted light optical microscope (Figure 17). Figure 22 clearly indicates that the RM is the weak zone in the RCA-PCC system and a crack can easily pass through this zone. The weak nature of the RM is considered the main reason for the strength reduction for RCA-PCC. This finding further emphasizes that controlling the RMC in RCA should be considered as an important step to produce high quality RCA-PCC mixtures.

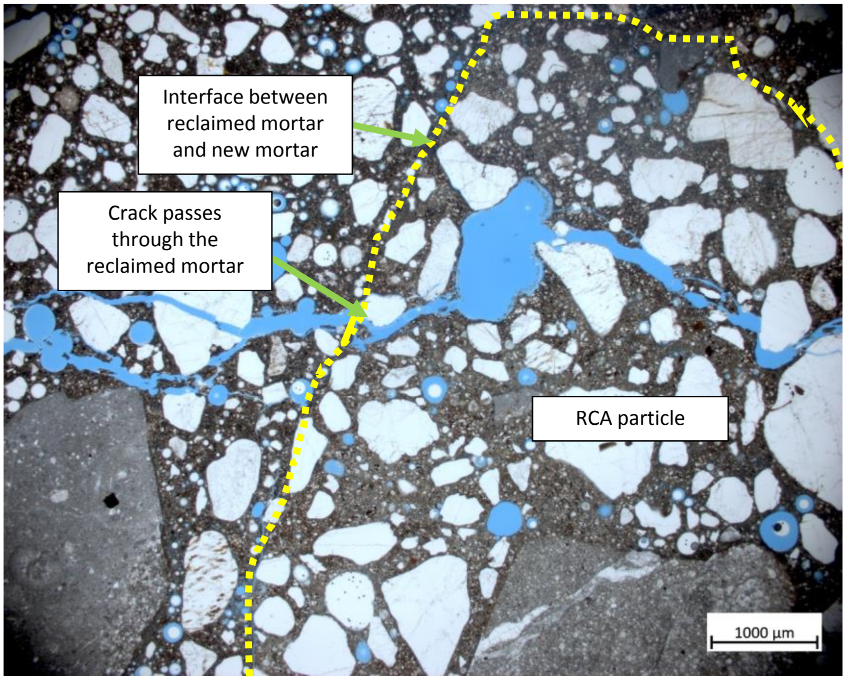


Figure 22. Crack Passes through RM (Observing the Cracked Thin Section Specimen Prepared from the I-35 RCA Core).

Determination of Mechanical Properties

The mechanical properties including CS, MOE, and STS of the cores taken from each pavement location were tested. Selective cores (with no cracks or steel) were trimmed to 8 in. in length and 4 in. in diameter (if the original sample was 6 in. in diameter) using a table saw and a coring machine. All the mechanical properties tests were completed using a 224-kip MTS machine according to the corresponding ASTM testing procedures. Figure 23 shows pictures of test set-up.

(a) CS test set-up (b) MOE test set-up (c) STS test set-up

Figure 23. Mechanical Properties Tests Set-up.

The CS, or f_c' , of the specimen was calculated according to the following equation:

$$f_c' = \frac{4P}{\pi D^2}$$

Where
P = ultimate load
D = diameter of the sample

The MOE of the specimen was obtained by:

$$MOE = \frac{(S_2 - S_1)}{\varepsilon_2 - 0.000050}$$

Where
S_1 = stress corresponding to an averaged longitudinal strain, ε_1, of 50 millionths
S_2 = stress corresponding to 40 percent of ultimate load
ε_2 = averaged longitudinal strain produced by stress S_2

The STS of the specimen was computed as:

$$STS = \frac{2P}{\pi LD}$$

Where
L = length of the sample

Table 9 summarizes the measured mechanical properties of the core samples. The percent changes of CS, MOE, and STS of the RCA-PCC compared to control PCC were listed in the last column in Table 10. The MOE and STS of the RCA section were invariably lower than its control section for both I-40 and I-35 pavements, and their percent change of RCA properties relative to control properties was close between I-35 and I-40 pavements. The test results were inconsistent in terms of CS though. The I-40 section indicated that the RCA section had higher averaged CS compared to the control section, while an opposite conclusion was made for the I-35 section. Due to the limited amount of testing data, statistical significances could not be established.

Table 9. Mechanical Properties Test Results.

Mechanical properties	Section	Location	Specimen ID	Values (psi)	Averaged value (psi)	Coefficient of variance	% Change of RCA properties relative to control properties
CS	I-40 EB, Control section	Segment 1	I40-1-3	6017	6442	9%	–
CS	I-40 EB, Control section	Segment 2	I40-2-3	6866	6442	9%	–
CS	I-40 EB, RCA section	Segment 3	I40-3-3	6907	6907	–	+7%
CS	I-35 SB, RCA section	Segment 1	I35SB-1-3	7647	6735	19%	−11%
CS	I-35 SB, RCA section	Segment 2	I35SB-3-3	5822	6735	19%	−11%
CS	I-35 NB, Control section	Segment 1	I35NB-1-2	6885	7594	13%	–
CS	I-35 NB, Control section	Segment 2	I35NB-2-3	8303	7594	13%	–
MOE	I-40 EB, Control section	Segment 1	I40-1-4	5395181	5209931	5%	–
MOE	I-40 EB, Control section	Segment 2	I40-2-4	5024681	5209931	5%	–
MOE	I-40 EB, RCA section	Segment 3	I40-3-4	4665177	4665177	–	−10%
MOE	I-35 SB, RCA section	Segment 1	I35SB-1-4	4984399	5643621	17%	−13%
MOE	I-35 SB, RCA section	Segment 2	I35SB-3-4	6302843	5643621	17%	−13%
MOE	I-35 NB, Control section	Segment 1	I35NB-1-3	6639748	6492053	3%	–
MOE	I-35 NB, Control section	Segment 2	I35NB-2-4	6344358	6492053	3%	–
STS	I-40 EB, Control section	Segment 1	I40-1-5	1064	1079	2%	–
STS	I-40 EB, Control section	Segment 2	I40-2-5	1094	1079	2%	–
STS	I-40 EB, RCA section	Segment 3	I40-3-5	885	885	–	−18%
STS	I-35 SB, RCA section	Segment 1	I35SB-1-5	869	898	5%	−19%
STS	I-35 SB, RCA section	Segment 2	I35SB-3-5	926	898	5%	−19%
STS	I-35 NB, Control section	Segment 1	I35NB-1-4	892	1102	27%	–
STS	I-35 NB, Control section	Segment 2	I35NB-2-5	1312	1102	27%	–

– Not applicable

A negative percentage change means a decrease in properties for RCA-PCC compared to the control PCC and vice-versa

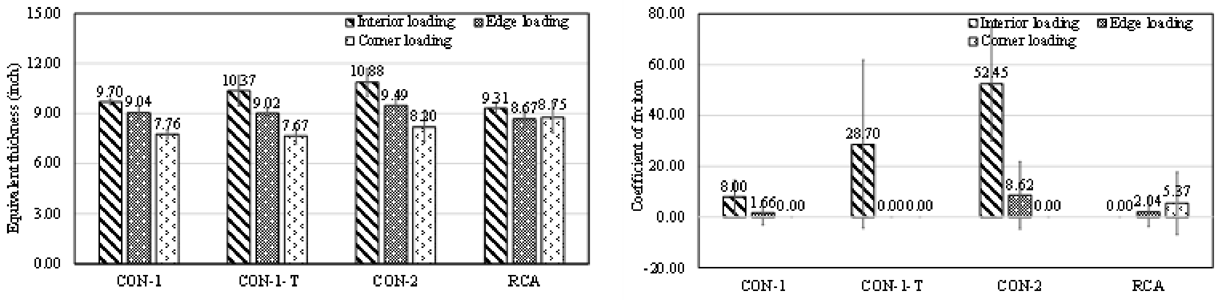
In addition to the mechanical properties, the CoTE of the concrete specimens was measured according to AASHTO T336. The CoTEs are 6.49×10^{-6}/°F and 5.83×10^{-6}/°F for the I-40 RCA section and I-40 control section specimens, respectively; the CoTE of the I-35 RCA core specimen is 7.13×10^{-6}/°F and that of the control section is 5.61×10^{-6}/°F. Both the I-40 and I-35 results show that the RCA-PCC higher CoTE compared to the control PCC. This finding matches the finding from literature.

FWD Analysis

The FWD data collected from the field investigation were analyzed. The FWD sensor were located at 0, 12, 24, 36, 48, and 60 in. away from the loading plate; an additional rear sensor that was located at a distance of 12 in. back of the loading plate was used to get an additional data point when the FWD is leaving the joint/crack. Four pavement structural parameters, including the pavement LTE, equivalent thickness (h_{e-p}), coefficient of friction (μ), and DE, were computed based on the procedures in Appendix D.

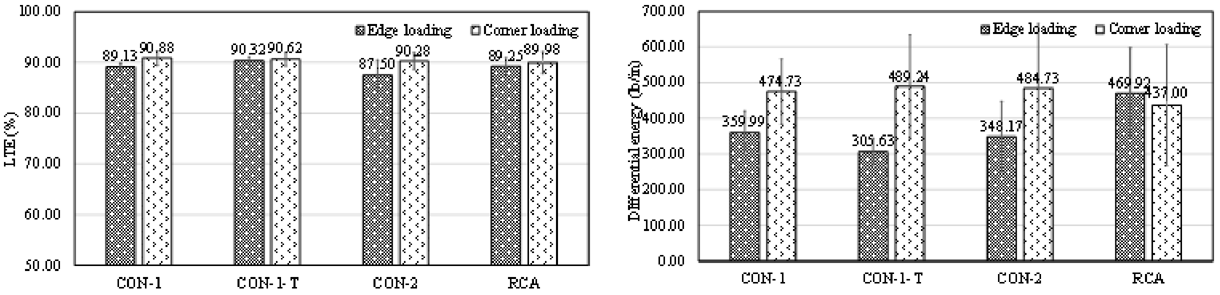
The FWD analysis results are shown in Figure 24 and Figure 25 for the I-40 JPCP and I-35 CRCP sections, respectively. Figure 24 compares the averaged values for the equivalent thickness, coefficient of friction, LTE, and DE for the I-40 JPCP sections. CON-1-T is the additional FWD test performed in the afternoon on the same segment (Segment 1) of the CON-1. The pavement tested in the afternoon had a higher temperature, so the effect of pavement temperature could be evaluated by comparing the results of CON-1-T with CON-1. Figure 24 shows that the corner always shows lowest structural integrity (i.e., lower equivalent thicknesses, lower coefficient of friction, and higher DE), followed by pavement edge and interior regions. This finding confirmed the existence of separation between the slab and the base at the corner. As expected, the RCA section shows slightly poor field performance compared to the control section. The relatively poor performance of the RCA section is manifested by the lower equivalent thickness for interior and edge loadings, lower coefficient of friction for interior loading, and higher DE for edge loading (when comparing RCA to CON-1 and CON-1-T). For corner loading, the RCA section turns out to have higher equivalent thickness and higher coefficient of friction compared to all the control sections though. From Figure 24(d), the difference between the DE of the edge loading and that of the corner loading appears to be negligible for the RCA section, while CON-1 and CON-1-T both exhibit a much lower DE for edge loading than that for corner loading. For CON-2, although the averaged DE value for edge loading seems similar with that for corner loading, it suffers a high coefficient of variation. These findings from Figure 24(d) suggest that the structural integrity at the edge of the slab for CON-1 was still good, while CON-2 has started to loss some structural integrity. Regarding the RCA section, it is inferred from the results that the structural integrity has already been lost.

An evaluation of data through statistical approaches was performed to more robustly assess the data. Two-sample t-test by assuming unequal variance was performed. Table 10 shows the results. From Table 10, the equivalent thickness (h_{e-p}) comparisons with a P-value lower than 0.05 are CON-2 and RCA for interior loading and CON-1 and RCA for corner loading. These results indicate that the equivalent thickness of CON-2 is significantly higher than that of RCA at interior of the slab and the equivalent thickness of RCA is significantly higher than that of CON-1 at corner. For the coefficient of friction, the significantly different comparisons are CON-1 and RCA and CON-2 and RCA at interior, meaning the coefficients of friction for both CON-1 and CON-2 are significantly higher than that of RCA at slab interior location. Regarding the LTE, the only significant comparison is the CON-1 and CON-1-T at edge loading, which indicates the CON-1-T has a statistically higher LTE than the CON-1. Also, the differential energy comparisons show that the results for the CON-1 is statistically lower than the RCA, and the CON-1-T is statistically lower than the CON-1. The statistical analysis confirmed the previous conclusion (i.e., relatively lower degree of performance of the RCA section in comparison with the control section). Also, the change in temperature did result in a considerable difference in stiffness of the pavement. The higher the pavement temperature, the stiffer the pavement.



(a) Equivalent thickness

(b) Coefficient of friction



(c) LTE

(d) Differential energy

Figure 24. FWD Results for JPCP Sections.

Table 10. Two-Sample t-Test Results (by Assuming Unequal Variance) for JPCP with a Significance Level of 0.05.

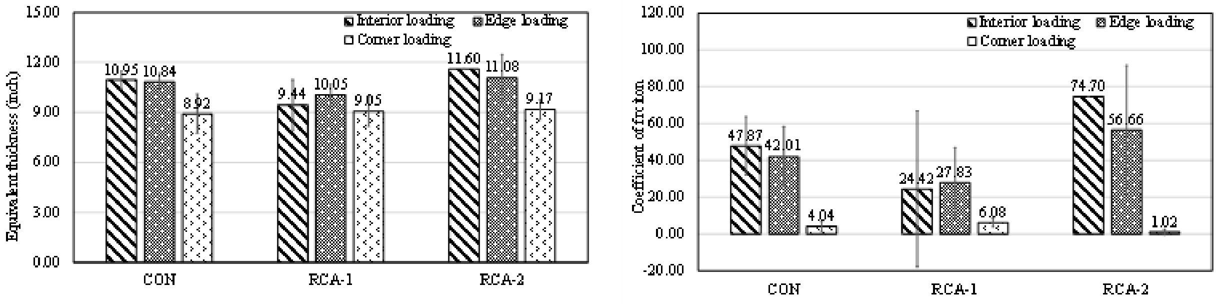
Parameter	FWD loading position	CON-1 & RCA	CON-2 & RCA	CON-1 & CON-1-T
P-value for h_e	Interior	0.08158	0.02771^*	0.12164
P-value for h_e	Corner	0.00964^*	0.10773	0.31918
P-value for μ	Interior	0.04490^*	0.02823^*	0.14307
P-value for μ	Corner	0.12843	0.12843	–
P-value for LTE	Edge	0.42793	0.06804	0.00302^*
P-value for LTE	Corner	0.16845	0.37883	0.35004
P-value for DE	Edge	0.02619^*	0.35128	0.02699^*
P-value for DE	Corner	0.29186	0.28585	0.40511

Note: the null hypothesis is the parameter between two segments is equal. A less than 0.05 P-value means that there is 95 percent confidence to reject the null hypothesis, which suggests that the parameter of the two segments is significantly different.

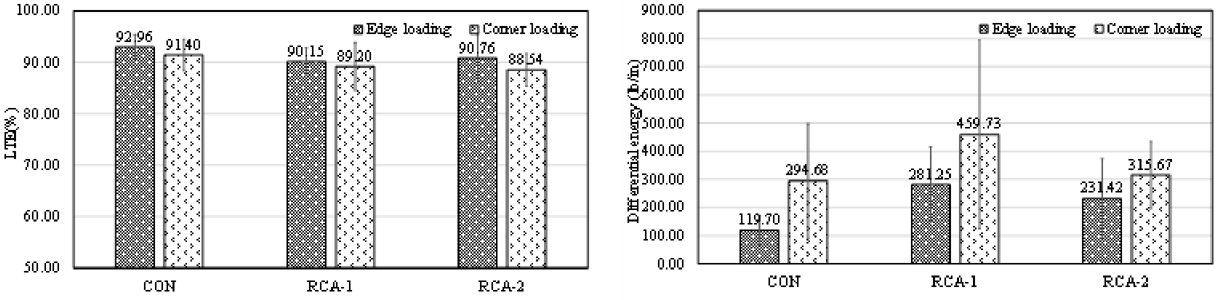
*indicates statistically significant comparison

– no data

Figure 25 shows the averaged values for the equivalent thickness, coefficient of friction, LTE, and DE for the CRCP testing sections. The results for the equivalent thickness and coefficient of friction indicate that the first RCA segment (RCA-1) had slightly lower structural integrity than the control section. Although the second RCA segment (RCA-2) shows higher equivalent thickness and coefficient of friction compared to the control, the data population for RCA-2 is limited so the results might be less convincing. For the LTE and DE, it seems that both the RCA sections have lower LTE and higher DE than the control section. Table 11 shows the two-sample t-test results. For the equivalent thickness comparison, the difference between CON and RCA-1 is significant for edge loading (i.e., the equivalent thickness of CON is significantly higher than that of RCA-1). The P-value for RCA-1 and RCA-2 is also below 0.05, suggesting RCA-2 has significantly higher equivalent thickness than that of RCA-1 at edge. Based on the P-values for coefficient of friction, CON and RCA-2 both have significantly higher coefficient of friction than the RCA-1 section at pavement edge while the coefficient of friction of RCA-2 section is significantly lower than that of either CON or RCA-1 at corner locations. The DE and LTE results generally indicate that the crack of CON is significantly stiffer than the RCA sections. Based on the results, there is some evidence showing the RCA CRCP section is not performing as well as the control section, but this evidence is much weaker compared to the I-40 JPCP case.



(a) Equivalent thickness (b) Coefficient of friction



(c) LTE (d) Differential energy

Figure 25. FWD Results for CRCP Sections.

Table 11. Two-Sample t-Test Results (by Assuming Unequal Variance) for CRCP with a Significance Level of 0.05.

Parameter	FWD loading position	CON & RCA-1	CON & RCA-2	RCA-1 & RCA-2
P value for h_e	Edge	$<0.00001^*$	0.49632	0.02621^*
P value for h_e	Corner	0.24382	0.13832	0.30545
P value for μ	Edge	$<0.00001^*$	0.17123	0.01719^*
P value for μ	Corner	0.17606	0.02752^*	0.01045^*
P value for LTE	Edge	$<0.00001^*$	0.07723	0.34061
P value for LTE	Corner	0.003419^*	0.00588^*	0.28840
P value for DE	Edge	$<0.00001^*$	0.01370^*	0.14850
P value for DE	Corner	0.00234^*	0.31227	0.01136^*

Note: the analysis for the interior loading was not performed because the data points were not sufficient
*indicates statistically significant comparison

Pavement Surface Condition

Pavement surface condition survey data for the I-40 JPCP section were provided by the Oklahoma DOT. The data were collected on July 10, 2016. A comparison of pavement performances between the control section and RCA section was made by statistically assessing different distress measurements (two-sample t-test results by assuming unequal variance with a significance level of 0.05). Table 12 presents the results. From Table 12, the RCA section clearly shows relatively lower degree of performances compared to the control section as it has statistically higher international roughness index (IRI) and faulting values. It also has a much higher amount of patching areas and higher numbers of slabs with a high severity transverse crack than the control section. According to FHWA (2004), use of RCA with smaller maximum aggregate size could adversely affect the aggregate's interlock load transfer capacity; the higher faulting of the RCA section is attributed to the use of RCA with reduced maximum size. From Table 12, again, no D-cracking issues were reported. The condition survey results match very well with researchers' field observation.

Table 12. Pavement Surface Condition for the I-40 Sections.

Condition indicator	Description	Unit	I40 EB CON section	I-40 RCA section	Statistically significant?
IRI_Avg	Mean IRI value of both wheel paths	in/mile	87.82	169	Yes
Faulting_Avg	Mean fault in right wheel path	inch	0.07	0.11	Yes
Faulting_Max	Maximum fault in right wheel path	inch	0.14	0.22	Yes
Faulting_Corner	Number of faulted joints (not to exceed Joints)	Count/mile	294.31	342.22	na
Joints	Number of joints	Count/mile	367.56	384.44	na
PCPatch	Area of PC patching on JCP or CRCP	sq. ft.	3019.40	20571.11	na
TransSlab_1	Number of slabs with a low severity transverse crack	Count/mile	0	0	na
TransSlab_2	Number of slabs with a high severity transverse crack	Count/mile	0.33	14.44	na
LongSlab_1	Number of slabs with a low severity longitudinal crack	Count/mile	17.06	5.56	na
LongSlab_2	Number of slabs with a high severity longitudinal crack	Count/mile	61.87	73.33	na
Corner_1	Number of slabs with low severity corner breaks	Count/mile	0	0	na
Corner_2	Number of slabs with high severity corner breaks	Count/mile	4.68	1.11	na
Spall_1	Number of joints with low severity spalling	Count/mile	2.68	2.22	na
Spall_2	Number of joints with high severity spalling	Count/mile	25.75	18.89	na
Multicrk_1	Number of slabs with more than one low severity crack	Count/mile	0	0	na
Multicrk_2	Number of slabs with more than one high severity crack	Count/mile	4.35	1.11	na
DCrack_1	Number of joints with low severity D-cracking	Count/mile	0	0	na
DCrack_2	Number of joints with high severity D-cracking	Count/mile	0	0	na

na = not available

Table 13 shows the pavement surface condition survey data for the I-35 CRCP sections. Despite of higher IRI and higher patching areas, the amount of punchout was less for the control section when compared to the RCA section. Accordingly, it seems that no clear conclusion on which pavement section had better performances can be made.

Table 13. Pavement Surface Condition for the I-35 Sections.

Condition indicator	Descriptions	Unit	I35 NB CON section	I-35 SB section	Statistically significant?
IRI_Avg	Mean IRI value of both wheel paths	in/mile	92.08	87.44	Yes
PCPatch	Area of PC patching on JCP or CRCP	sq. ft.	327.40	18.40	na
LongCRC_1	Length of low severity longitudinal cracks not to exceed 53 ft	feet	0.00	0.00	na
LongCRC_2	Length of high severity longitudinal cracks not to exceed 53 ft	feet	2.20	0.00	na
Punch_1	Number of low severity punchouts	Count/ mile	0.00	0.00	na
Punch_2	Number of medium severity punchouts	Count/ mile	0.00	0.20	na
Punch_3	Number of high severity punchouts	Count/ mile	0.60	2.00	na

na = not available

The data presented in the previous sections indicate that the RCA JPCP section exhibited relatively lower degree of performance compared to the control JPCP section, which is manifested by lower equivalent thickness, lower coefficient of friction, and higher IRI and faulting values of RCA JPCP section than the control JPCP section. The RCA CRCP section showed some evidence of not performing as well as the control CRCP section, but such evidence is not as strong as the JPCP case. The addition of RCA into PCC yields reduced MOE based on the mechanical property test results; from researchers' previous simulation work (Shi 2018) and the FWD results from this study (Figure 24(d)), PCC slabs with lower MOE yield increased DE. According to pavement ME models (AASHTO 2003), higher DE causes higher faulting and base erosion and eventually deteriorates pavement structural integrity. The higher faulting value for RCA JPCP is correlated well with the higher DE determined from the FWD data. The results for coefficient of friction (Figure 24(b)) infer that the RCA section already developed a higher amount of base damage compared to the control section. The RCA seems to have a less detrimental effect on the CRCP section because the CRCP section rests on a much stronger asphalt base compared to the relatively weak soil base for the JPCP. The steel reinforcement is believed to help protect the base and reduce negative effects caused by use of RCA in PCC slab (such as those caused by higher CoTE and drying shrinkage). In addition, a previous research indicates that CRCP slabs with lower MOE could potentially develop tighter transverse cracking; a reduction in transverse cracking width helps maintain high LTE, which results in better pavement performance (Shi et al. 2018b). However, it is also known that RCA (especially with reduced maximum aggregate size) is more vulnerable to aggregate interlock wear-out, so the actual effect of RCA on the ability of a CRCP transverse crack to transfer load remains questionable, which warrants future research effort.

These Oklahoma RCA pavements were constructed in the 1980s, when pavement engineers did not gain sufficient understanding of RCA-PCC from material characterization and pavement design perspectives. Since then, much research effort has been made on use RCA for pavement applications. Several researchers recommended to use shorter joint spacing to minimize transverse cracking caused by increased shrinkage and thermal properties of RCA-PCC (Anderson et al. 2009). However, no such modification concerning joint spacing was adopted in the reconstruction of the I-40 RCA section. The neglect of using a shorter joint spacing might have resulted in the greater number of transverse cracking in the I-40 RCA section (Table 12), and this might have further worsened its overall performances. In addition, failure to use of good base support and strong load transfer also contributed to the unsatisfied performance of the RCA JPCP in Oklahoma.

Based on the findings from this study, it is again verified that good base support, strong load transfer, and shorter joint spacing are essential considerations for designing and constructing RCA JPCP. CRCP might be more suitable for implementing RCA-PCC; it could better protect the base from erosion caused by higher DE and help restrain high drying and thermal volume change of RCA-PCC.

CONCLUSIONS

Like many other state DOTs, ODOT is committed to protect and enhance human and natural environment while developing a safe, economical, and effective transportation system. The state has great interests in using recycled and reusable waste materials, such as RCA, RAP, recycled tires, crushed glass, and recycled carpets, in infrastructural constructions.

The first objective of this research was to develop strategies for increasing the use of recycled materials in ODOT transportation construction projects after incorporating view points and perspective of all the stakeholders in the decision-making process. A review of available recycled materials and their current industry practice for infrastructure projects was carried out. These recycled materials include RCA, RAP, RAS, recycled rubber, recycled glass, and recycled carpet. Based on the survey sent to the representative from the ODOT to inquire general interest of using different recycled materials and potential challenges of using these materials, using RCA as an aggregate replacement was identified as the primary interest for Oklahoma infrastructure projects in this project. Based on the collected survey results from the nationally recognized RCA researchers together with the findings from existing literature, the following recommendations are summarized for reducing the detrimental effects of RCA on PCCP performance:

- Keeping RCA stockpiles at saturated status is important due to RCA's high-water demand nature.
- A short joint spacing is needed to compensate the negative effects caused by the higher CoTE of the RCA-PCCP.
- Building a strong base and subgrade support is highly recommended for RCA-PCCP, since the reduced MOE would induce higher DE to the support, causing higher slab faulting and base erosion.
- RCA-PCCP may not be placed in hot summer due to the higher shrinkage potential of RCA-PCC slab.
- Dowel bars are usually recommended for pavement built with RCA concrete to compensate the lower aggregate interlock.
- Use RCA in PCC may cause steel to corrode faster than normal, so RCA might need to be washed before mixing. Use of corrosion resistant steels can be helpful.

In addition, a life cycle assessment addressing all the three aspects of sustainability (i.e., economic, social, and environmental) was performed to do a comparative assessment between RCA-PCCP and plain PCCP and project the benefits of using RCA-PCC. Researchers concluded that the use of RCA-PCC to make pavement could offer benefits covering all three aspects of sustainability such as cost savings, energy savings, conservation of good quality virgin aggregates, reduction in consumption of landfill space, and reduction in greenhouse emissions. These benefits are expected to be magnified in future with a growing demand of environmental awareness and gradual reduction of good quality local virgin aggregate sources.

The second objective of the study was to evaluate the long-term performance of PCCP constructed with RCA. The performances of selected JPCP and CRCP sections were extensively assessed through various tests covering different aspects, which includes visual survey, determination of mechanical properties, petrographic examination, and evaluation of the existing base. The major findings of this study are:

- The MOE and STS of the RCA sections were invariably lower than their corresponding control sections for the both JPCP and CRCP pavements. The percent reduction of MOE and STS relative to control was close between the JPCP and CRCP. Although, the RCA-PCC JPCP sections showed a slightly higher average CS compared to the control section, the RCA-PCC CRCP sections showed lower CS compared to the control section (normal trend).
- The petrographic study via thin section observation proves to be an effective technique to study microstructural features and crack pattern/propagation in RCA-PCC. The RM is regarded as the primary weak zone, through which cracks can easily pass.
- The surface condition survey data and the FWD results are complementary in nature. The results generally indicate that the RCA JPCP section exhibited relatively lower degree of performances compared to the control JPCP section, but such trend is not valid for the CRCP sections. The relatively good performance of the RCA CRCP section is because that CRCP can better protect the base from erosion and help restrain high drying and thermal volume change of RCA-PCC.

Based on the findings, it is verified that good base support, strong load transfer, and shorter joint spacing are essential design considerations for JPCP made of RCA-PCC. CRCP might be more suitable for implementing RCA-PCC; CRCP could better protect the base from erosion caused by higher DE and help restrain high drying and thermal volume change of RCA-PCC.

The findings from the two research objectives clearly reveal that there are widespread benefits of using recycled and reused waste materials in construction in Oklahoma. In particular, use of RCA for concrete pavement applications not only is a technically sound concept, but also can lead to significant sustainability benefits; the good long-term performance of the two studied RCA-PCCP sections shall strengthen the idea of using RCA in PCC. It is also suggested to research the use of RAP in PCC for pavement applications followed by implementation plans. The performing agency has recently completed a research project on use of RAP to make PCC for TxDOT and found that use of RAP-PCC for pavement applications is practically viable. As local aggregate source is being further diminished, use of recycled aggregates (e.g., RCA, RAP) would provide a cost-effective solution for concrete paving projects.

APPENDIX A: LEVEL OF INTEREST OF VARIOUS RECYCLED MATERIALS IN OKLAHOMA

Researchers identified and interviewed some experienced industry professionals from ODOT and Oklahoma recycling industry with the help of the Project Director, Bryan Hurst, and the Research Engineer, Teresa Stephens. Valuable information and opinions on the level of interest of various recycled materials in Oklahoma and their potential challenges have been collected and summarized below:

- RCA:
    - RCA produced from ODOT projects can be good material, but issues exist about the local demolition waste handlers and the poor quality of RCA that they have offered up in the past. The RCA issue is essentially a quality control (QC) issue. Until now, high quality RCA is scarce in Oklahoma (Scott Seiter, ODOT).
    - RCA has routinely been used as aggregate base in Oklahoma. It has to meet regular specifications, and it does if the contractor exercises good QC practices. The approach of using the aggregate durability index (AASHTO T 210) as one of the screening tools for RCA may be unusual in the arena of national practice, but is considered one of the better screening tools that others should consider adopting (Scott Seiter, ODOT).
    - Old concrete having aggregates with durability issue and concrete with D-cracking should be avoided in RCA. RCA is a very good option for those states, ship aggregate with long haul and aggregate is costly. On some concrete pavement projects in Oklahoma, we have recycled almost 100 percent concrete pavement for aggregates base (Waseem Fazal, FHWA).
    - A cost benefit analysis of different concrete recycling options can be useful (Waseem Fazal, FHWA).
    - There are several producers in the area of low-quality RCA. It is hard to get high-quality RCA even for bases without recycling an existing roadway on site. They almost always contain clay and fail the fine portion of the aggregate durability test. RCA has been mostly used as a base or for shouldering. It has not been used in PCC for several years. In terms of using RCA in PCC, specifications would have to be changed to allow it in PCC as it can’t pass the current specifications. The major pass/fail test for aggregate base is the fine aggregate durability test (Javier Rojas-Pochyla, ODOT).
- RAP—It is necessary to evaluate the quantity and availability of RAP in Oklahoma before finding applications for their use. Currently, there is not a huge quantity of excess RAP just looking for a use. There is no restriction on RAP in WMA in Oklahoma (Scott Seiter, ODOT).
- Rubber—The ODOT does not want to use coarsely ground rubber tires in asphalt concrete. The DOT’s next focus on rubber asphalt mixes will be to evaluate the

technology being offered up by Red Clark as the approach appears to be practical and economical (Scott Seiter, ODOT).

APPENDIX B: EXPERT OPINIONS ON USE OF RCA IN PCC FOR PAVEMENT APPLICATIONS

This appendix presents the collected information on use of RCA in PCC for pavement applications. This information was obtained through RCA webinars and interviews from nationally recognized experts.

National Concrete Pavement Center Webinars

Researchers attended three webinars offered by National Concrete Pavement Technology Center. The webinar materials were developed in cooperation with and sponsored by FHWA.

The first webinar is titled "Construction Considerations in Concrete Pavement Recycling." It was presented by Gary Fick from Trinity Construction Management Service. Key points from the webinar are summarized as below:

- Jaw crusher can be used as a primary crusher. It allows feeding of larger sized pieces of broken concrete (24 in.) and helps to separate steel from the broken concrete. It can also minimize fines. Impact crusher might be the most common crusher for RCA applications. Before using an impact crusher, most steel should be removed from old concrete. The impact crusher has a smaller feed size (approx. 12 in. minus).
- RCA Stockpiles must be kept moist (above SSD) to avoid absorption during the batching process.
- Fines in RCA sources come predominantly from the underlying materials.
- In RCA, #4 and larger particles composed of RM. RCA containing higher RMC has a potential for higher absorption and might cause problems for pavements. Further crushing can break these particles down, but it usually leads to inefficiencies.
- RCA use and applications depend on:
  - Availability of space for recycling.
  - Environmental permitting restrictions.
  - Cost of virgin materials.
- Specifications should allow RCA wherever possible in terms of both base and PCC applications:
  - Modify durability requirements (LA abrasion, sodium sulfate, C666, etc.) to allow RCA usage.
  - Reduce the specification for the low end of the material passing the #200.
  - Gradation QC should be performed at the same frequency as for virgin aggregates.

The second webinar is related to environmental considerations in concrete recycling. It was presented by Tara Cavalline from UNC-Charlotte.

The benefits of concrete recycling are justified at the beginning of the presentation:

- Economic benefits:
    - Cost savings.
    - Benefits to project execution.
    - Potential performance improvements.
- Environmental benefits:
    - Conservation of aggregates, energy.
    - Reduction of landfill use.
    - Reduction of greenhouse gases.
    - Sequestration of carbon.
- Societal benefits:
    - Reduced land use.
    - Reduced impact to landscape.
    - Potential reduction in traffic/noise (particularly with on-site recycling).

It was mentioned in the webinar that the concrete recycling can have the following potential environmental impacts:

- Water quality:
    - Contaminants in runoff and drainage.
    - Alkalinity, chemical contaminates, other.
    - Transported sediments.
- Air quality:
    - Equipment emissions.
    - Fugitive dust.
- Noise, other local impacts:
    - Additional processing, handing.
    - Traffic.
- Waste generation and disposition—Solids, wastewater, slurries, residuals.

Regarding the quality of source concrete, it is typically only a concern if RCA is used in new concrete (RCA-PCC application):

- Oil typically not present in an amount to cause concern.
- Chlorides can promote corrosion of dowels, reinforcing bars (no reported corrosion issues in RCA field studies conducted to date).

- Sulfates could cause expansion and damage (No reported corrosion issues in RCA field studies conducted to date).
- Other distresses from the recycled pavement such as ASR, D-cracking need to be prevented from reoccurrence.

The webinar also investigated the RCA Leachate/Runoff characteristics:

- The leachate from in-situ RCA sources and runoff from stockpiles include Alkaline (high pH) and chemical contaminates such as: salts, heavy metals, metalloids, and polycyclic aromatic hydrocarbons.
- RCA leachate/runoff typically can be an issue when offsite or commercial sources of concrete are used for recycling.
- RCA leachate/runoff can cause formation of deposits in and around pavement drainage systems.
- RCA leachate/runoff can generate tufa (calcium carbonate precipitate) and insoluble residue.
- Use of RCA in concrete mixtures mitigates water quality issues associated with leaching. Water quality issues associated with use of RCA in bound applications have not been reported. However, RCA concrete tends to leach higher level metals than conventional concrete.

In conclusion, there appears to be no negative environmental effects from using RCA that significantly offset the positive environmental effect of reduced use of virgin aggregate and landfills.

The third webinar features the case studies in concrete pavement recycling. Mark Snyder was the instructor. Based on evaluation of existing RCA-PCC field sections (summarized in Task 1), the following recommendations on using RCA in PCC for pavement application have been made in this webinar:

- Pavement structural design:
  - Consider high CoTE and shrinkage of RCA-PCC, and adjust panel length according to this. Adjust sealant reservoir dimensions and sealant materials as well.
  - Pavement built with RCA may need higher reinforcing quantities.
  - Reduced aggregate interlock of RCA may need to take into account (i.e., dowels may be required).
  - Evaluate abrasion resistance (surface friction and wear) of RCA-PCCP.
- RCA in mixture design:
  - Quality requirements and properties.
  - Generally, the same as for PCC with virgin aggregate.
  - Exception: sulfate soundness (unreliable for RCA).
  - Strategies to prevent reoccurrence of material-related distress.

    - ASR: use lithium, class F fly ash and/or slag cement and limit RCA fine; reduce water access (joint sealing, drains, etc.).
    - D-cracking: reduce coarse aggregate top size; reduce moisture exposure; test effectiveness of all treatments before construction.

- RCA in mixture design proportioning:
  - Consider lower specific gravity and higher absorption capacity of RCA.
  - Consider higher strength variability of the produced RCA-PCC.
  - To maintain workability, add 5–15 percent water or use admixtures.
  - Verity air content requirements (adjust for air in RM).
  - Trial mixtures are essential.

Interviews from Nationally Recognized Experts

Table 14 summarizes the responses from some nationally recognized experts.

Table 14. Survey Response from Nationally Recognized Experts on RCA-PCC.

Expert	Survey Reponses
Brent Burwell, ACPA	• Standard practice should be to try to use only RCA produced on site from existing pavement. Off-site facilities may be accepting for commercial or industrial concrete that may be contaminated (flooring, ceramics, etc.)
Richard Henderson, SCC Materials	• RCA-PCC is sometimes hard to place and is more difficult finish. It sets quicker, and RCA needs to wash to remove fines. • Recycling RCA in PCC is feasible at central locations but difficult when remote crushing is performed. • Using RCA-PCC in the lower lift of a two-lift pavement needs careful analysis as it sets quicker, which could affect bonding and second lift placement.
Jiong Hu, University of Nebraska-Lincoln	• One hundred percent coarse RCA can be used provided RCA is in good quality. Fifty percent fine RCA may be also allowed based on concerns on high fines and related potential workability and durability issue. • Higher absorption and rougher surface require appropriate mixture design adjustment for appropriate workability. Potential breakdown of aggregate particles (residual cement paste) during mixing and construction might be a problem. • Gradation, absorption, residual cement paste content, chemical analysis (for potential ASR, sulfate, Cl deterioration) are major considerations for the mix design. • RCA is still not widely used in PCC as compared to RAP in HMA, and I think we need a group effort to overcome the two obstacles: lack of agency regulation and lack of appropriate and quality control measure for RCA to be used in PCC and to push more use of RCA in PCC.
David Lange, University of Illinois	• RCA based PCC has been used in projects at O'Hare Airport, and built on research for the Illinois Department of Transportation. More recently, the Illinois Tollway has incorporated the knowledge from the O'Hare research into their projects (not published). All the research has focused primarily on the coarse RCA. The fine RCA in PCC has been included in the research, but not included in field trials. The RCA fines are better suited for alternative applications. • In the O'Hare application, the direct benefits include reduction in the use of virgin aggregates and reduction in the disposal costs associated with disposing the waste concrete. O'Hare Airport generates a significant amount of concrete waste from normal maintenance and from the ongoing effort to reconfigure the runways as a part of the

Expert	Survey Reponses
	O'Hare Modernization Program. The waste concrete cannot be store on the airfield which means that the material must either be repurposed or landfilled. Disposal costs can be excessive given the geographic location of the airfield. As a result, the waste concrete is crushed for coarse RCA to be used for aggregate base or concrete aggregate. • In the research at O'Hare Airport, all levels in the pavement process were supportive in using the coarse RCA in in pavements. The RCA was produced from demolished airfield pavement, so it was consistent in composition and free of other construction debris. Finally, the concrete producer followed recommendations to maintain a high moisture content in the RCA. • The primary field trial at O'Hare Airport consisted of two adjacent pours of RCA-based concrete and the typical concrete with only virgin aggregate. The RCA-based concrete met all of the required strength and workability parameters. Embedded sensors in the pavements did not indicate any difference in performance over a year of monitoring. The field trial pavements are almost nine years old and are visually indistinguishable from each other.
Richard Meininger, FHWA	• It is feasible to use RCA in plain concrete pavement in most all regions (stainless steel dowel bars may be needed if the RCA has chlorides), and in reinforced concrete pavement in warmer regions where deicing salts are not used. I think the chloride content of some RCAs would disqualify it for use in reinforced concrete because of the corrosion risk. • Mostly it is the coarse size RCA that can be used, but some fine aggregate RCA may work in some cases. RCA should be saturated prior to mixing the concrete and its potential internal curing properties should be investigated. RCA aggregate concrete will have a lower E-modulus and may have more strain capacity (before cracking) than higher modulus concretes. This should also be researched in a fatigue loading environment. • Obstacles to be investigated include slump loss if the RCA is not saturated, chlorides that may accelerate corrosion of steel, aggregate interlock at cracks and undoweled joints, dowel bar socketing issues at joints with repeated heavy truck traffic, and friction performance if RCA is used as the fine aggregate. • Including mortar in the RCA can be allowed if it is of good quality. • If the RCA is coming from known quality concrete sources (highway and airfield pavements), it should be good quality and/or the source quality can be investigated. If the RCA is from mixed concrete rubble, QC will be difficult with the more variable RCA. • The primary crushing is often done with a large jaw crusher and that impact crushers are best as secondary crushers at shattering the concrete and extracting any steel ahead of final screening and removing of any steel with magnets and/or by manual picking. • Some plants in Houston have unbound aggregate products and cement-treated base with the RCA crushed from mixed rubble and slabs. They are considering putting in a wash plant to make concrete aggregate.
Andy Naranjo, TxDOT	• TxDOT routinely uses RCA in concrete pavement and structures. TxDOT allows the use of 100 percent RCA as coarse aggregate. Only issues were when high percent of RCA fine aggregate was used, which created high water demand and hard to finish mixes. Once stockpile moistures were controlled better, the issues went away. However, TxDOT now limits the use of RCA fines to 20 percent of the fine aggregate. • TxDOT has seen no issue with having mortar remained on the RCA. If the mortar survives the crusher, then the bond between the mortar and rock is excellent and should not create any negative issues. • Houston and Dallas Districts routinely use RCA.
Karthik Obla, NRMCA	• The major obstacles for the use of RCA in PCC for pavement applications include: Specification do not allow, cost of processing RCA, and some performance degradation but that could be designed for.

Expert	Survey Reponses
	• Higher Water demand, lower strength, higher rapid chloride permeability, higher ASR expansion are the major detrimental effects of using RCA on PCC. Generally, fines make it worse.
Leandro Francisco Moretti Sanchez, University of Ottawa	• Regarding cost and sustainability, one of the most important parameters for RCA mixtures is the amount and quality of the residual mortar attached to the aggregate particles. First, the residual mortar changes the physicochemical properties of the RCA mix, and second, if the residual mortar is not accounted for in the new mix, the RCA concrete would use a much higher amount of cement than a comparable conventional concrete mixture, which somewhat offsets its sustainable character. That's exactly why new mix-design methods that account for the residual mortar should be used to proportion recycled concrete mixtures with suitable properties in the fresh and hardened states. • The strength is not a big deal for RCA concrete, especially when conventional mechanical properties are targeted (i.e., 20 to 45 MPa). Otherwise, there are still a number of issues and uncertainties regarding the fresh state behavior (i.e., higher viscosity, consistency and absorption when compared to conventional mixes) and the long term/durability performance of RCA concrete (i.e., higher permeability, lower resistivity, lower resistance against scaling and freezing and thawing).
Leif Wathne, ACPA	• The only challenges have to do with presence of deleterious materials leading to materials related distresses (MRD). We have to ensure that the existing concrete does not exhibit significant potential for ASR and other MRDs. The in-place concrete has to be properly and adequately characterized to avoid the potential for MRDs in the new concrete. • In general, workability and finishability are impacted negatively, because of the more porous and rough texture of RCA. Water demand also tends to be slightly greater for the same reason. Hardened concrete properties are also impacted; strength and stiffness are typically lower, shrinkage, creep, and permeability all tend to be greater (again depending on the properties of the existing concrete).

APPENDIX C: LIFE CYCLE ASSESSMENT OF RCA-PCCP: A CASE STUDY

This appendix presents a life cycle assessment to compare an RCA-PCCP and a plain PCCP from different aspects of sustainability, namely the economic impact, social impact, and environmental impact. The life cycle assessment was carried out through an EIO-LCA approach. The EIO-LCA theory was proposed by the Nobel Prize winner Wassily Leontief and was further developed by the Green Design Institute at Carnegie Mellon University. The EIO-LCA approach has been widely used in various research areas, which includes the field of pavement sustainability (Mukhopadhyay and Shi 2017; Rew et al. 2018; Shi et al. 2018a).

Pavement Performance

To ensure the compared pavement structures have equivalent performance is the key for a valid life cycle assessment comparison. Presence of RM has been reported to be one of major reasons to cause RCA to have material properties deviated from the virgin aggregate; these changed material properties could lead to significant detrimental impacts on pavement performance based on the literature findings and the field investigation of this research (presented in Objective 2). The focus of this life cycle assessment was to evaluate pavement structures whose varying parameters are PCC layer properties only. Although increasing the level of base support is commonly recommended to enhance RCA-PCCP performance, no research has yet been done to specially design a base for which RCA-PCCP could have comparable performance with plain PCCP. It is also difficult to set up a scenario that an RCA-PCCP with a thicker PCC layer has equivalent performance with a plain PCCP due to immaturity of the design tools and lack of such field data:

1. The existing concrete pavement design tools such as AASHTO 1993 and Pavement ME Design fail to consider all the changes in concrete material properties by RCA addition in the pavement design procedure, so determination of equivalent pavement structures using pavement simulation approaches appears not to be feasible for the time being.
2. There is a considerable amount of existing RCA-PCCPs in the United States, but most of these existing RCA-PCCPs were constructed using the same PCC thickness as their control pavement.

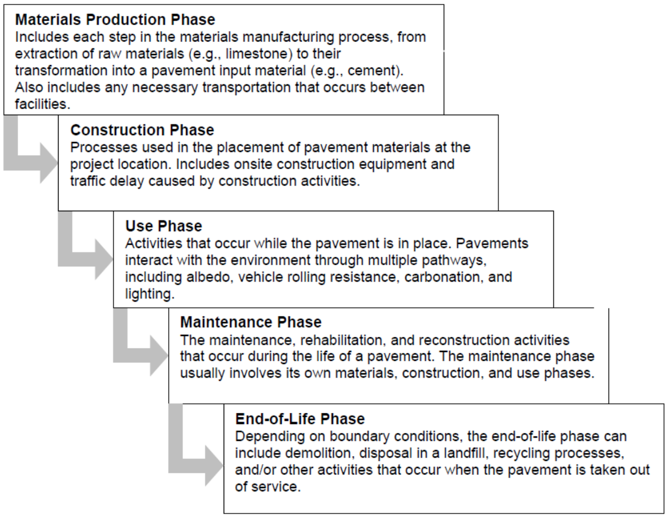
Accordingly, this life cycle assessment focuses an RCA-PCCP and a plain PCCP with the same structure design (i.e., same PCC slab thickness and support conditions). The relatively poorer pavement performance of the RCA-PCCP is reflected by its shorter pavement service life.

In this life cycle assessment, the hypothetical RCA-PCCP and the plain PCCPs were created to best mimic the I-40 RCA and control sections investigated in Objective 2. Both the RCA-PCCP and the plain PCCPs were assumed to be 8-mile long 48 ft wide (two lanes in each direction; each lane is 12 ft wide) with the same PCC layer thickness (10 in.). Same mix designs of the I-40 pavements were used for the two hypothetical pavements in this life cycle assessment. Table 6 presents the mix designs.

To reasonably determine the pavement service life of the studied pavements, the long-time performance data for the RCA-PCCPs and plain PCC (non-RCA) pavements collected and analyzed by Reza et al. (2018a) were used. In Reza et al.'s (2018a) work, the long-term performances of approximately 212 miles of RCA-PCCP sections and 212 miles of plain PCCP sections covering various case studies in the United States were extensively studied through a statistical analysis. Based on their findings, the mean time to reach the condition of major concrete pavement rehabilitation was found to be 27 years for RCA-PCCP and 32 years for plain PCCP. Accordingly, the pavement service life for the RCA-PCCP and the plain PCCP in this life cycle assessment study was set at 27 years and 32 years, respectively. For the sake of comparison, the analysis periods of the plain PCCP and RCA-PCCP were both 27 years in this life cycle assessment. The remaining service life of the plain PCCP counted toward the end-of-life salvage value.

Phase of Life Cycle Assessment

A pavement life cycle includes raw materials production, construction, use, maintenance, and end-of-life (Santero et al. 2010). Figure 26 summarizes each phase.



Materials Production Phase
Includes each step in the materials manufacturing process, from extraction of raw materials (e.g., limestone) to their transformation into a pavement input material (e.g., cement). Also includes any necessary transportation that occurs between facilities.

Construction Phase
Processes used in the placement of pavement materials at the project location. Includes onsite construction equipment and traffic delay caused by construction activities.

Use Phase
Activities that occur while the pavement is in place. Pavements interact with the environment through multiple pathways, including albedo, vehicle rolling resistance, carbonation, and lighting.

Maintenance Phase
The maintenance, rehabilitation, and reconstruction activities that occur during the life of a pavement. The maintenance phase usually involves its own materials, construction, and use phases.

End-of-Life Phase
Depending on boundary conditions, the end-of-life phase can include demolition, disposal in a landfill, recycling processes, and/or other activities that occur when the pavement is taken out of service.

Figure 26. Difference Phases of Pavement Life Cycle (Santero et al. 2010).

Each phase of the life cycle poses a unique burden on economy, environment, and society. A complete life cycle assessment shall incorporate all these phases, but it is usually very difficult to include all of them, especially for the field of pavement LCA that is still maturing. Three critical phases were included in this EIO-LCA. These phases are raw material production and construction, use, and end-of-life. Although the maintenance phase was not considered since the end-of-life is defined as the first CRP for the pavements, the life cycle assessment presented in this study is still regarded as one of the most comprehensive studies in the field of pavement LCA.

Materials Production and Construction Phase

Based on the pavement structure and mix design defined, the amount of raw materials needed to construct the plain PCCP and the RCA-PCCP was calculated. The costs of the raw materials including cement, fly ash, virgin coarse aggregate, and virgin fine aggregate were obtained from the RSMeans Database (RS Means 2018). The cost data (total cost including overhead and profit) are modified values by considering the city cost index for Oklahoma City, so they represent the mean local raw material costs at Oklahoma City in year 2018. The cost of water is found on the Utilities Department of OKC's website (OKC Utilities Department, na). An important assumption of this study is that both the plain PCCP and the RCA-PCCP are reconstructions of two old plain PCCPs that were 9-in. thick, 8-mile long, and 48 ft wide. The RCA is the demolition waste of the old PCCP, so a zero material cost is assumed for the RCA. If not recycled and reused, the remaining pavement debris would be landfilled for both the plain PCCP and the RCA-PCCP cases. The costs associated with transporting pavement debris to the landfill site and the landfill fee will be analyzed later in this section. Table 15 summarizes the raw material unit price, the amount of raw materials needed, and the total cost for each raw material.

Table 15. Summary of Raw Material Costs.

Material	Unit Price	Amount Needed (ton) Plain PCCP	Amount Needed (ton) RCA-PCCP	Material Cost Plain PCCP	Material Cost RCA-PCCP
Cement	\$259.3/ton	14987	14987	\$3,886,519	\$3,886,519
Fly ash	\$60.7/ton	3598	3598	\$218,484	\$218,484
Virgin coarse aggregate	\$24.9/ton	58323	0	\$1,452,933	\$0
Virgin fine aggregate	\$22.0/ton	37734	35356	\$830,158	\$777,843
Water	\$0.71/ton	7847	7847	\$5,589	\$5,589
RCA	\$0/ton	0	53035	\$0	\$0

The total weight of pavement slab debris was calculated as 111,676 ton. For the plain PCCP case, all the debris will be transported to a landfill site, which is assumed to be 50 miles away with a hauling cost of \$0.35/ton/mile. For the RCA-PCCP case, the remaining concrete debris that needs to be hauled away is 58,641 ton (111,676−53,035=58,641). A landfill fee of \$2/ton is used for both cases. The hauling fee and landfill fee are reasonably assumed by referring several previous publications on pavement LCA (Shi et al. 2018a; Verian et al. 2013). While processing RCA from pavement debris could yield additional cost, such cost is considered negligible compared to the large cost associated with demolishing and removing old pavements. The old pavement demolition cost is not included in the life cycle assessment because this cost is identical for both cases. In addition to hauling RCA to the landfill site, virgin coarse aggregate is assumed to be transported from an aggregate supply, which is 30 miles way. The cost for hauling virgin aggregates to the ready-mix concrete plant is $0.35/ton/mile as well. Table 16 summarizes the costs associated with hauling materials and landfilling concrete debris.

Table 16. Summary of Costs Associated with Hauling Materials and Landfilling Concrete Debris.

Cost	Plain PCCP case	RCA-PCCP case
Haul virgin aggregates from the aggregate supply to the plant	$1,008,599	$371,243
Haul concrete debris away to the landfill site	$1,954,327	$1,026,219
Landfill concrete debris	$223,352	$117,282

According to the RSMeans Database (RS Means 2018), the average PCCP construction cost at OKC in 2018 is $3.56/s.y. This yields a total cost of $803,047 for constructing a PCCP with 8 miles long and 48 ft wide (which was used in this study). Construction of RCA-PCCP can be successfully done with conventional concrete pavement construction equipment, so it is reasonably assumed that the total cost of the RCA-PCCP is also $803,047.

Use Phase

The major components evaluated in the use phase of this life cycle assessment are vehicle operation costs (VOC), which are the costs relevant to vehicle repair and maintenance, fuel consumption, and tire wear. Impacts of the use phase (especially that contributed by fuel consumption) on pavement sustainability can be huge. According to Hakkinen and Makela (1996), a 0.1 to 0.5 percent decrease in fuel consumption due to beneficial pavement characteristics would produce sustainable benefits comparable to the total benefits from all the other phases of the pavement life cycle.

The VOC for the two PCCP cases were estimated using the VOC model developed under NCHRP 720 (Chatti and Zaabar 2012). In this study, the vehicle operating costs at the project level were calculated by directly using the developed software from the NCHRP 720. The inputs for the VOC analysis at the project level that are different between the plain PCCP and the RCA-PCCP cases are pavement IRI and texture depth. An initial IRI of 63 in./mile was assumed for both the plain PCCP and the RCA-PCCP cases. According to Reza and Wilde's (2017) statistical analysis results, the mean IRI increase over time is 1.7553 in./mile/year for plain PCCPs and 2.0423 in./mile/year for RCA-PCCPs in the United States. These values were used in this study to compute the pavement IRIs for each year. For the texture depth, the ODOT made the texture depth measurement for the I-40 pavement's control and RCA sections in 2016. The measured texture depth was 0.73 mm for the control section and 0.84 mm for the RCA-PCC section; these two values were adopted and held constant with time in the VOC analysis. The VOC model also requires having annual average daily traffic (AADT) and traffic distribution as inputs. According to the ODOT AADT Traffic Counts database (ODOT, na), the AADT for the I-40 pavement was

49,200 for the year of 2017. A traffic growth rate of 1.5 percent was used to obtain the AADT for each during the entire analysis period for both cases. The traffic distribution is listed in Table 17, which is based on the data provided by the ODOT.

Table 17. Traffic Distribution of the I-40 Pavement Section (Estimated Based on the Data from the ODOT).

Traffic category	Distribution
Small car	21.33%
Medium car	21.33%
Large car	21.33%
Light delivery car	22.86%
Light goods vehicle	1.71%
Four-wheel drive	1.71%
Light truck	0.37%
Medium truck	2.23%
Heavy truck	6.56%
Articulated truck	0.27%
Mini bus	0.06%
Light bus	0.06%
Medium bus	0.06%
Heavy bus	0.06%
Coach	0.06%
Total	100%

The VOC of the plain PCCP and the RCA-PCCP cases for each year during the analysis period were calculated and converted to present worth (i.e., year 1’s value) using the following equation:

$$\mathrm{P} = \frac{\mathrm{F}}{(1+i)^n}$$

Where
P = present worth
F = future worth
i = annual discount rate, i = 1.5 percent is used in this study
n = number of years

Table 18 shows the cumulative VOC for the 27-year analysis period. From Table 18, because of higher pavement IRIs, the rougher RCA-PCCP induces higher damage to vehicle tires and causes higher fuel consumption. Both the cases yield same vehicle repair and maintenance cost. This is because the difference in the pavement roughness between the plain PCCP and RCA-PCCP is not significant enough for the model to yield different results.

Table 18. Cumulative VOC for the Case Study.

Cost	Plain PCCP	RCA-PCCP
Repair and maintenance	$281,806,174	$281,806,174
Tire Consumption	$60,968,158	$61,122,108
Fuel Consumption	$861,016,189	$863,418,887

End-of-Life Phase

As previously mentioned, the pavement service life for the plain PCCP and the RCA-PCCP was set at 32 years and 27 years, respectively. However, for the sake of comparison, a 27-year analysis period was used for both cases. The remaining service life of the plain PCCP counted toward the end-of-life salvage value. The salvage value is given by (Reza et al. 2018b):

$$\text{Salvage value} = \frac{\text{Remaining service life}}{\text{Expected service life}} \times \text{Initial cost}$$

The salvage value that is associated with year 27 was then converted to present worth at the year 1. The salvage values for different categories including raw materials and paving are tabulated in Table 19.

Table 19. Summary of the Salvage Value for the Plain PCCP Case.

Sector	Salvage Value for the 27th year	Salvage Value Converted to the 1th year
Cement	$607,269	$412,348
Fly ash	$34,138	$23,180
Virgin coarse aggregate	$227,021	$154,152
Virgin fine aggregate	$129,712	$88,077
Water	$873	$593
Paving	$125,476	$85,201

EIO-LCA Procedure and Output Flows

After the economic inputs were obtained for all the phases, a U.S. 2002 purchaser model in the EIO-LCA was used to calculate the resources, energy requirement, and the environmental emissions for each phase, respectively. The total impact of pavement life cycle was then achieved by summing up the impact of each phase.

In the EIO-LCA, the economic values for various sectors representing different categories in the life cycle inventory were input to the model. The LCA inventory output flows including economic activity, energy, conventional air pollution, greenhouse gases, land use, toxic releases, transportation, and water withdrawal were obtained.

Materials Production and Construction Phase

Table 20 tabulates the economic inputs for different sectors at the material production and construction phase. Table 21 shows the LCA inventory output flows.

Table 20. Economic Inputs for Different Sectors at the Material Production and Construction Phase.

Sector	Sector Group	Detailed Sector	Economic Inputs (Dollars) Plain PCCP	Economic Inputs (Dollars) RCA-PCCP
Cement	Plastic, rubber, and nonmetallic mineral products	Cement manufacturing	\$3,886,519	\$3,886,519
Fly ash	Plastic, rubber, and nonmetallic mineral products	Cement manufacturing	\$218,484	\$218,484
Virgin coarse aggregate	Mining and utilities	Stone mining and quarrying	\$1,452,933	\$0
Virgin fine aggregate	Mining and utilities	Sand, gravel, clay, and refractory mining	\$830,158	\$777,843
Water	Mining and utilities	Water, sewage, and other systems	\$5,589	\$5,589
Paving	Construction	Other nonresidential structure	\$803,047	\$803,047
Haul (virgin aggregates)	Trade, transportation, and communications media	Truck transportation	\$1,008,599	\$371,243
Haul (RCA aggregates away)	Trade, transportation, and communications media	Truck transportation	\$1,954,327	\$1,026,219
RCA landfill	Management, administrative, and waste services	Waste management and remediation services	\$223,352	\$117,282

Table 21 to Table 28 show the benefits of use RCA in PCCP in all the LCA categories. The production of the RCA-PCCP could save 31 percent of cost, consume 16 percent less energy, emit 21 percent less conventional air pollution and 9 percent less greenhouse gases, use 26 percent less land, release 10 percent less toxic substances, occupy 15 percent less transportation, and save 33 percent of water. These achieved sustainable benefits are due to the less consumption of virgin aggregate, less virgin aggregate transported to the ready-mix plant, and less concrete debris transported to and deposited in the landfill site.

Table 21. Summary of Output Flows for Life Cycle Inventory at the Material Production and Construction Phase: Economic Activity (Million Dollars).

LCA category	Values—Plain PCCP	Values—RCA-PCCP	The RCA value minus the plain value over the plain value times 100%
Total	***20.1***	***13.9***	***−31%***
Direct economic	15.6	10.8	−31%

Table 22. Summary of Output Flows for Life Cycle Inventory at the Material Production and Construction Phase: Energy (TJ).

LCA category	Values—Plain PCCP	Values—RCA-PCCP	The RCA value minus the plain value over the plain value times 100%
Total	353.1	297.3	−16%
Coal	152	147	−3%
Natural gas	37.8	30.7	−19%
Petroleum-based fuel	116	76.2	−34%
Biomass/waste fuel	20.1	19.5	−3%
31% non-fossil fuel electricity	27.2	23.9	−12%

Table 23. Summary of Output Flows for Life Cycle Inventory at the Material Production and Construction Phase: Conventional Air Pollution (Ton).

LCA category	Values—Plain PCCP	Values—RCA-PCCP	The RCA value minus the plain value over the plain value times 100%
Total	***473.4***	***373.3***	***−21%***
CO	124.0	97.6	−21%
NH_3	0.8	0.6	−23%
NOx	159.0	130.0	−18%
PM_{10}	67.0	37.8	−44%
$PM_{2.5}$	18.7	12.4	−34%
SO_2	90.3	85.2	−6%
Volatile organic compounds	13.6	9.7	−29%

Table 24. Summary of Output Flows for Life Cycle Inventory at the Material Production and Construction Phase: Greenhouse Gases (Ton CO_2 eq).

LCA category	Values—Plain PCCP	Values—RCA-PCCP	The RCA value minus the plain value over the plain value times 100%
Total	***45961***	***41697***	***−9%***
CO_2 fossil	24700	21000	−15%
CO_2 process	19800	19700	−1%
CH_4	1330	892	−33%
N_2O	65.7	50	−24%
HFC/PFCs	65.5	54.6	−17%

Table 25. Summary of Output Flows for Life Cycle Inventory at the Material Production and Construction Phase: Land Use (kha).

LCA category	Values—Plain PCCP	Values—RCA-PCCP	The RCA value minus the plain value over the plain value times 100%
Total	***0.353***	***0.26***	***−26%***

Table 26. Summary of Output Flows for Life Cycle Inventory at the Material Production and Construction Phase: Toxic Releases (kg).

LCA category	Values—Plain PCCP	Values—RCA-PCCP	The RCA value minus the plain value over the plain value times 100%
Total	***8394.7***	***7545.4***	***−10%***
Fugitive air	87.6	66.1	−25%
Stack	2790	2660	−5%
Total air	2880	2720	−6%
Surface water	116	92.6	−20%
Underground water	102	68.2	−33%
Land	1890	1560	−17%
Off-site	406	286	−30%
POTW metal	2.12	1.61	−24%
POTW non-metal	121	91	−25%

Table 27. Summary of Output Flows for Life Cycle Inventory at the Material Production and Construction Phase: Transportation (×10^6 ton-km).

LCA category	Values—Plain PCCP	Values—RCA-PCCP	The RCA value minus the plain value over the plain value times 100%
Total	***160***	***136***	***−15%***
Air	0.00583	0.00456	−22%
Oil Pipe	1.99	1.16	−42%
Gas pipe	1.36	1.20	−12%
Rail	12.20	9.10	−25%
Truck	19.20	11.90	−38%
Water	4.99	1.64	−67%
International air	0.01	0.01	−25%
International water	120	111	−8%

Table 28. Summary of Output Flows for Life Cycle Inventory at the Material Production and Construction Phase: Water Withdrawal (kGal).

LCA category	Values—Plain PCCP	Values—RCA-PCCP	The RCA value minus the plain value over the plain value times 100%
Total	***186000***	***124000***	***−33%***

Use Phase

Table 29 presents the economic inputs for different sectors at the use phase, and Table 30 to Table 37 show the LCA inventory output flows. Based on the results, the RCA-PCCP was slightly less sustainable compared to the plain PCCP during the use phase. The rougher pavement surface of the RCA-PCCP causes higher tire and fuel consumption for vehicles, which poses higher negative impacts. However, compared to the numerous amounts of economic, social, and environmental burden generated during the use phase of the pavements, the difference of the output flows is very small (i.e., the difference is below 1 percent for all the categories).

Table 29. Economic Inputs for Different Sectors at the Use Phase.

Categories	Sector group	Detailed sector	Economic inputs (dollars) Plain PCCP	Economic inputs (dollars) RCA-PCCP
Repair and maintenance	Vehicle and Other Transportation Equipment	Motor Vehicle Parts Manufacturing	\$281,806,174	\$281,806,174
Tire Consumption	Plastic, rubber, and nonmetallic mineral products	Tire manufacturing	\$60,968,158	\$61,122,108
Fuel Consumption	Petroleum and basic chemical	Petroleum refineries	\$861,016,189	\$863,418,887

Table 30. Summary of Output Flows for Life Cycle Inventory at the Use Phase: Economic Activity (Million Dollars).

LCA category	Values—Plain PCCP	Values—RCA-PCCP	The RCA value minus the plain value over the plain value times 100%
Total	***2450***	***2460***	***0.41%***
Direct economic	1860	1860	0.00%

Table 31. Summary of Output Flows for Life Cycle Inventory at the Use Phase: Energy (TJ).

LCA category	Values—Plain PCCP	Values—RCA-PCCP	The RCA value minus the plain value over the plain value times 100%
Total	***15673***	***15693***	***0.13%***
Coal	2230	2230	0.00%
Natural gas	5760	5770	0.17%
Petroleum-based fuel	5580	5590	0.18%
Biomass/waste fuel	583	583	0.00%
31% non-fossil fuel electricity	1520	1520	0.00%

Table 32. Summary of Output Flows for Life Cycle Inventory at the Use Phase: Conventional Air Pollution (Ton).

LCA category	Values—Plain PCCP	Values—RCA-PCCP	The RCA value minus the plain value over the plain value times 100%
Total	***11561.5***	***11582.5***	***0.18%***
CO	3810.0	3820.0	0.26%
NH_3	53.5	53.5	0.00%
NOx	2780.0	2780.0	0.00%
PM_{10}	552.0	553.0	0.18%
$PM_{2.5}$	216.0	216.0	0.00%
SO_2	2010.0	2020.0	0.50%
Volatile organic compounds	2140.0	2140.0	0.00%

Table 33. Summary of Output Flows for Life Cycle Inventory at the Use Phase: Greenhouse Gases (Ton CO_2 eq).

LCA category	Values—Plain PCCP	Values—RCA-PCCP	The RCA value minus the plain value over the plain value times 100%
Total	***1269780***	***1271800***	***0.16%***
CO_2 fossil	866000	868000	0.23%
CO_2 process	111000	111000	0.00%
CH_4	277000	277000	0.00%
N_2O	6350	6360	0.16%
HFC/PFCs	9430	9440	0.11%

Table 34. Summary of Output Flows for Life Cycle Inventory at the Use Phase: Land Use (kha).

LCA category	Values—Plain PCCP	Values—RCA-PCCP	The RCA value minus the plain value over the plain value times 100%
Total	***33.7***	***33.7***	***0.00%***

Table 35. Summary of Output Flows for Life Cycle Inventory at the Use Phase: Toxic Releases (kg).

LCA category	Values—Plain PCCP	Values—RCA-PCCP	The RCA value minus the plain value over the plain value times 100%
Total	***590164***	***590365***	***0.03%***
Fugitive air	37600	37700	0.27%
Stack	121000	121000	0.00%
Total air	159000	159000	0.00%
Surface water	26900	26900	0.00%
Underground water	17600	17600	0.00%
Land	132000	132000	0.00%
Off-site	67800	67800	0.00%
POTW metal	564	565	0.18%
POTW non-metal	27700	27800	0.36%

Table 36. Summary of Output Flows for Life Cycle Inventory at the Use Phase: Transportation ($\times 10^6$ ton-km).

LCA category	Values—Plain PCCP	Values—RCA-PCCP	The RCA value minus the plain value over the plain value times 100%
Total	***15061.106***	***15061.207***	***0.00%***
Air	0.996	0.997	0.10%
Oil Pipe	1690	1690	0.00%
Gas pipe	69.9	70	0.14%
Rail	439	439	0.00%
Truck	383	383	0.00%
Water	276	276	0.00%
International air	2.21	2.21	0.00%
International water	12200	12200	0.00%

Table 37. Summary of Output Flows for Life Cycle Inventory at the Use Phase: Water Withdrawal (kGal).

LCA category	Values—Plain PCCP	Values—RCA-PCCP	The RCA value minus the plain value over the plain value times 100%
Total	***7920000***	***7930000***	***0.13%***

End-of-Use

The salvage values of the plain PCCP case for different sectors were input in the model (Table 38). Table 39 to Table 46 present the resources, energy requirement, and the environmental emissions associated with the salvage values. Since the salvage value is deducted money from the total money, the LCA output flows in Table 39 to Table 46 are all negative. They will be deducted from the total life cycle output flows of the plain PCCP. Because the service life of the plain PCCP is equal to the analysis period, 0 salvage value is defined and no output flows for the end-of-use were deducted.

Table 38. Economic Inputs for Different Sectors at the End-of-Use Phase.

Sector	Sector group	Detailed sector	Amount of activity (dollars) Salvage value at the end of life cycle	Amount of activity (dollars) Converted to the value at year 1
Cement	Plastic, rubber, and nonmetallic mineral products	Cement manufacturing	$607,269	$412,348
Fly ash	Plastic, rubber, and nonmetallic mineral products	Cement manufacturing	$34,138	$23,180
Virgin coarse aggregate	Mining and utilities	Stone mining and quarrying	$227,021	$154,152
Virgin fine aggregate	Mining and utilities	Sand, gravel, clay, and refractory mining	$129,712	$88,077
Water	Mining and utilities	Water, sewage, and other systems	$873	$593
Paving	Construction	Other nonresidential structure	$125,476	$85,201

Table 39. Summary of Output Flows for Life Cycle Inventory at the End-of-Use Phase: Economic Activity (Million Dollars).

LCA category	Salvage value for the plain PCCP
Total	***−2.2***
Direct economic	−1.7

Table 40. Summary of Output Flows for Life Cycle Inventory at the End-of-Use Phase: Energy (TJ).

LCA category	Salvage value for the plain PCCP
Total	−46.3
Coal	−23.3
Natural gas	−5.1
Petroleum-based fuel	−10.9
Biomass/waste fuel	−3.0
31% non-fossil fuel electricity	−4.0

Table 41. Summary of Output Flows for Life Cycle Inventory at the End-of-Use Phase: Conventional Air Pollution (Ton).

LCA category	Salvage value for the plain PCCP
Total	***−61.3***
CO	−14.6
NH_3	−0.1
NOx	−19.7
PM_{10}	−9.1
$PM_{2.5}$	−2.7
SO_2	−13.7
Volatile organic compounds	−1.4

Table 42. Summary of Output Flows for Life Cycle Inventory at the End-of-Use Phase: Greenhouse Gases (Ton CO_2 eq).

LCA category	Salvage value for the plain PCCP
Total	***−6446.1***
CO_2 fossil	−3250.0
CO_2 process	−3080.0
CH_4	−99.5
N_2O	−8.0
HFC/PFCs	−8.7

Table 43. Summary of Output Flows for Life Cycle Inventory at the End-of-Use Phase: Land Use (kha).

LCA category	Salvage value for the plain PCCP
Total	***−0.041***

Table 44. Summary of Output Flows for Life Cycle Inventory at the End-of-Use Phase: Toxic Releases (kg).

LCA category	Salvage value for the plain PCCP
Total	***−1172.8***
Fugitive air	−10.1
Stack	−420.0
Total air	−431.0
Surface water	−14.5
Underground water	−8.2
Land	−234.0
Off-site	−41.2
POTW metal	−0.2
POTW non-metal	−13.6

Table 45. Summary of Output Flows for Life Cycle Inventory at the End-of-Use Phase: Transportation ($\times10^6$ ton-km).

LCA category	Salvage value for the plain PCCP
Total	***−23.32***
Air	−0.001
Oil Pipe	−0.147
Gas pipe	−0.201
Rail	−1.86
Truck	−2.96
Water	−0.75
International air	−0.002
International water	−17.4

Table 46. Summary of Output Flows for Life Cycle Inventory at the End-of-Use Phase: Water Withdrawal (kGal).

LCA category	Salvage value for the plain PCCP
Total	***−27300***

Entire Pavement Life Cycle

Table 47 to Table 54 show the total output flows for the entire pavement life cycle for the plain PCCP and the RCA-PCCP. From Table 47 through Table 54, recycling old concrete to make RCA-PCCP could reduce the unfavorable impacts in terms of energy consumption, conventional air pollution emission, land use, transportation movement, and water withdrawal compared to the plain PCCP. Although the percent differences between the RCA-PCCP and the plain PCCP cases are not significant, the difference in terms of net value can be huge if all the concrete pavement reconstruction in the United States uses RCA (given this case study only analyzed 8-mile long pavements). On the other hand, the RCA-PCCP yields higher economic burden during the entire pavement life cycle; it also releases slightly higher amounts of air pollution, greenhouse gases, and toxic substances. This is attributed to the higher tire and gasoline consumption because of the rougher pavement surface, and gasoline and tire productions lead to huge environmental burden.

Table 47. Summary of Output Flows for Life Cycle Inventory of the Entire Pavement Life Cycle: Economic Activity (Million Dollars).

LCA category	Values—Plain PCCP	Values—RCA-PCCP	The RCA value minus the plain value over the plain value times 100%
Total	***2467.9***	***2473.9***	***0.24%***
Direct economic	1873.9	1870.8	-0.17%

Table 48. Summary of Output Flows for Life Cycle Inventory of the Entire Pavement Life Cycle: Energy (TJ).

LCA category	Values—Plain PCCP	Values—RCA-PCCP	The RCA value minus the plain value over the plain value times 100%
Total	***16026.1***	***15990.3***	***-0.22%***
Coal	2358.7	2377.0	0.78%
Natural gas	5792.7	5800.7	0.14%
Petroleum-based fuel	5685.1	5666.2	-0.33%
Biomass/waste fuel	600.1	602.5	0.41%
31% non-fossil fuel electricity	1543.2	1543.9	0.04%

Table 49. Summary of Output Flows for Life Cycle Inventory of the Entire Pavement Life Cycle: Conventional Air Pollution (Ton).

LCA category	Values—Plain PCCP	Values—RCA-PCCP	The RCA value minus the plain value over the plain value times 100%
Total	***11973.6***	***11955.8***	***-0.15%***
CO	3919.4	3917.6	-0.05%
NH_3	54.2	54.1	-0.15%
NOx	2919.3	2910.0	-0.32%
PM_{10}	609.9	590.8	-3.13%
$PM_{2.5}$	232.1	228.4	-1.57%
SO_2	2086.6	2105.2	0.89%
Volatile organic compounds	2152.2	2149.7	-0.12%

Table 50. Summary of Output Flows for Life Cycle Inventory of the Entire Pavement Life Cycle: Greenhouse Gases (Ton CO_2 eq).

LCA category	Values—Plain PCCP	Values—RCA-PCCP	The RCA value minus the plain value over the plain value times 100%
Total	***1309295.1***	***1313496.6***	***0.32%***
CO_2 fossil	887450.0	889000.0	0.17%
CO_2 process	127720.0	130700.0	2.33%
CH_4	278230.5	277892.0	-0.12%
N_2O	6407.7	6410.0	0.04%
HFC/PFCs	9495.5	9494.6	-0.01%

Table 51. Summary of Output Flows for Life Cycle Inventory of the Entire Pavement Life Cycle: Land Use (kha).

LCA category	Values—Plain PCCP	Values—RCA-PCCP	The RCA value minus the plain value over the plain value times 100%
Total	***34.1***	***34.0***	***-0.27%***

Table 52. Summary of Output Flows for Life Cycle Inventory of the Entire Pavement Life Cycle: Toxic Releases (kg).

LCA category	Values—Plain PCCP	Values—RCA-PCCP	The RCA value minus the plain value over the plain value times 100%
Total	***597385.9***	***597910.4***	***0.09%***
Fugitive air	37677.5	37766.1	0.24%
Stack	123370.0	123660.0	0.24%
Total air	161449.0	161720.0	0.17%
Surface water	27001.5	26992.6	-0.03%
Underground water	17693.8	17668.2	-0.14%
Land	133656.0	133560.0	-0.07%
Off-site	68164.8	68086.0	-0.12%
POTW metal	565.9	566.6	0.13%
POTW non-metal	27807.4	27890.9	0.30%

Table 53. Summary of Output Flows for Life Cycle Inventory of the Entire Pavement Life Cycle: Transportation (×10^6 ton-km).

LCA category	Values—Plain PCCP	Values—RCA-PCCP	The RCA value minus the plain value over the plain value times 100%
Total	***15197.55***	***15197.22***	***0.00%***
Air	1.00	1.00	0.04%
Oil Pipe	1691.84	1691.16	-0.04%
Gas pipe	71.06	71.20	0.20%
Rail	449.34	448.10	-0.28%
Truck	399.24	394.90	-1.09%
Water	280.24	277.64	-0.93%
International air	2.22	2.22	-0.08%
International water	12302.60	12311.00	0.07%

Table 54. Summary of Output Flows for Life Cycle Inventory of the Entire Pavement Life Cycle: Water Withdrawal (kGal).

LCA category	Values—Plain PCCP	Values—RCA-PCCP	The RCA value minus the plain value over the plain value times 100%
Total	***8078700.0***	***8054000.0***	***-0.31%***

Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts

One of the indispensable steps of a life cycle assessment is to evaluate the potential impacts of output flows on environment and society. According to Bare (2002), the Tool for reduction and assessment of chemicals and other environmental impacts (TRACI) is an impact analysis tool that provides characterization factors for life cycle impact assessment, industrial ecology, and sustainability metrics. The characterization factors in the TRACI quantify the potential impacts that for the specific categories with common equivalence units. In this life cycle assessment, the TRACI factors were also the outputting results. The TRACI results for the plain PCCP and RCA-PCCP are compared in Table 55. Based on the results, use of RCA to reconstruct concrete pavement could have fewer negative impacts on the characterization factors including Human Health Particulate air, Smog air, Ecotoxicity (low), Ecotoxicity (high), Human Health Cancer (high), and Human Health NonCancer (high) compared to constructing concrete pavement using virgin aggregate.

Table 55. Life Cycle Impact Analysis Results.

TRACI	Values—Plain PCCP	Values—RCA-PCCP	The RCA value minus the plain value over the plain value times 100%
Global warming potential (ton CO_2 eq)	1319550	1321700	0.16%
Acidification air (ton SO_2 eq)	4528	4530	0.04%
Human health particulate air (ton PM_{10} eq)	1195	1174	-1.78%
Eutrophication air (ton N eq)	135	136	0.43%
Eutrophication water (ton N eq)	0.470	0.471	0.18%
Ozone depletion air (ton CFC-11 eq)	0.400	0.401	0.21%
Smog air (ton O_3 eq)	80195	80170	-0.03%
Ecotoxicity (low) (ton 2,4D)	37	36	-2.16%
Human health cancer (low) (ton benzene eq)	77	78	0.82%
Human Health NonCancer (low) (ton toluene eq)	48066	48320	0.53%
Ecotoxicity (high) (ton 2,4D)	38	38	-2.06%
Human Health Cancer (high) (ton benzene eq)	406	406	-0.19%
Human Health NonCancer (high) (ton benzene eq)	773530	760100	-1.74%

Conclusions

A life cycle assessment to compare an RCA-PCCP and a plain PCCP from different aspects of sustainability (economic impact, social impact, and environmental impact) was carried out through an economic input-output life cycle assessment approach. The output flows for life cycle inventory during the materials production and construction, use, and end-of-life phases were obtained and then assessed with the TRACI. The following conclusions are made from this life cycle assessment case study:

- The output flows result during the materials production and construction indicates that the RCA-PCCP yields significantly less economic, environmental, and social burden compared to the plain PCCP. The sustainability of the RCA-PCCP during the materials production and pavement construction is attributed to less consumption of virgin aggregate, less virgin aggregate transported to the ready-mix plant, and less concrete debris transported to and deposited in the landfill site.
- The RCA-PCCP was slightly less sustainable compared to the plain PCCP during the use phase. The rougher pavement surface of the RCA-PCCP causes higher tire and fuel consumption for vehicles, which poses higher negative impacts to the economy, environment, and society.

- The results of the total output flows and the characterization factors in the TRACI for the entire pavement life cycle are mixed. Although the benefits of using RCA in the materials production and construction phase are obvious, the higher amount of negative impacts during the use phase is more dominating in the entire life cycle. As a result, it cancels out the benefits achieved during the materials production and construction for the RCA-PCCP to some extent. But still, use of RCA to reconstruct concrete pavement could have fewer negative impacts on the characterization factors including Human Health Particulate air, Smog air, Ecotoxicity (low), Ecotoxicity (high), Human Health Cancer (high), and Human Health NonCancer (high) compared to building concrete pavement using virgin aggregates.

In conclusion, use of RCA in PCCP could potentially yield benefits in some of the sustainable categories. These benefits will only be magnified with a growing level of environmental awareness and further diminishment of local virgin aggregate sources in the future. Additionally, a modest $2/ton landfill cost was used to represent the cost in the Midwestern region of the United States. It also accounts for a bulk discount for the size of this project (Verian et al. 2013). The landfill costs could be significantly higher than this value nationwide. According to Bogert and Morris (1993), National Solid Wastes Management Association reports that tipping fees increased from an average of $8/ton in 1985 to $34.29/ton in 2004, with averages as high as $70.53/ton in the Northeast region.

APPENDIX D: DETERMINATION OF PAVEMENT STRUCTURAL PARAMETERS FROM FWD TEST RESULTS

The computation of pavement LTE, equivalent thickness (h_e), coefficient of friction (μ) and DE was performed using the FWD test data based on the following procedures.

Load Transfer Efficiency

LTE is used to quantify the transfer load across discontinuities (e.g., joint for JPCP, transverse crack for CRCP). If the joint/crack is performing perfectly, the LTE equals to 1. On the contrary, a 0 LTE means there is no integrity between the two pavement segments. The LTE is defined as:

$$LTE(\%) = \frac{w_{unload}}{w_{loaded}}$$

Where w_{unload} =unloaded deflection.
w_{loaded} = loaded deflection.

In the FWD data analysis, if the FWD is approaching a joint/crack, the LTE is calculated as:

$$LTE_A(\%) = \frac{w_1}{w_0}$$

Where w_0 = sensor deflection 0 in. away from the loading point.
w_1 = sensor deflection 12 in. away from the load point.

And if the FWD is leaving a joint/crack, the LTE is calculated as:

$$LTE_L(\%) = \frac{w_7}{w_0}$$

Where w_7 = sensor deflection −12 in. away from the load point (back sensor).

The LTE of a particular joint/crack can be determined by averaging LTE_A and LTE_L:

$$LTE(\%) = \frac{LTE_A + LTE_L}{2}$$

Equivalent Thickness

The concept of equivalent PCC thickness is applied to consider the effects of both PCC layer and base layer on pavement subgrade, as shown in Figure 27.

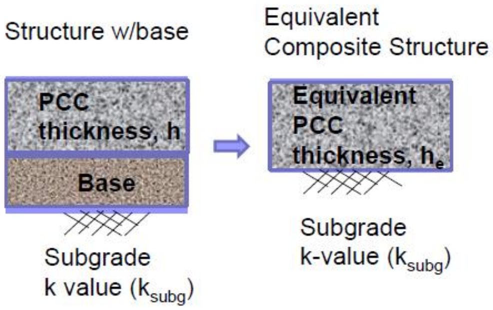


Figure 27. Equivalent PCC Thickness.

To determine the equivalent PCC thickness, the pavement basin area (BA) is computed based on measured FWD deflections:

$$BA = \frac{SS}{2 \times w_0}[w_0 + 2(w_1 + w_2 + w_3 + w_4) + w_5]$$

Where
SS = FWD sensor spacing (12 in.).
w_i = sensor deflection (i = 0 to 5).

The radius of relative stiffness (RRS) is then computed as:

$$l_e = a + b \times (BA) + c \times (BA)^2$$

Where a, b, c are coefficients obtained from the field correlation: a = 0.992, b = −0.2891, c = 0.0284.

The RRS along with the center plate deflection is useful to determine the foundation modulus of the subgrade reaction. Since the deflection data are associated with a rather high frequency loading cycle, the resulting calculation is assumed to result in a dynamic foundation modulus (k_{dyn}) as:

$$k_{dyn} = \frac{w_0^* P}{w_0 {l_e}^2}$$

Where
P = wheel load
w_0 = center plate deflection

$$w_0^* = \frac{1}{8}[1 + \left(\frac{1}{2\pi}\right)\left(\ln\left(\frac{a}{2l_e}\right) + \gamma - 1.25\right)\left(\frac{a}{l_e}\right)^2]$$

a = 5.9055 in.
γ = 0.5772156649

The equivalent thickness is then obtained using the following equation:

$$h_e = \sqrt[3]{\frac{12k_{dyn}(1-\nu^2){l_e}^4}{E_c}}$$

Where
v = Poisson's ratio (0.15)
E_c = concrete modulus of elasticity

Effective Coefficient of Friction (μ)

The coefficient of friction is determined as:

$$\mu = \frac{\sigma_{e-u} - \sigma_e[\frac{2h_{e-u}}{h_e} - 1]}{\frac{h_c}{12} + \sigma_v}$$

Where

$$\sigma_{e-u} = \frac{S_{e-u}P}{h_c^2}$$

$S_{e-u} = a + bl_u + cl_u^2$ (a = 0.0006, b = 0.0403 and c = −0.0002)

$$l_u = \sqrt[4]{\frac{E_c h_u^3}{12k_{DCP}(1-\nu^2)}}$$

k_{DCP} =DCP modulus of the subgrade reaction (assumed to be 120 pci)
h_u = Unbound PCC slab thickness
σ_v = load induced vertical pressure (0.7 psi)

$$\sigma_e = \frac{S_e P}{h_e^2}$$

$S_e = a + bl_e + cl_e^2$ (a = 0.0006, b = 0.0403 and c = −0.0002)

When the calculated μ is a negative value, μ = 0 is adopted.

Differential Energy

The DE is computed as:

$$DE = \frac{k_{dyn}}{2}\left(w_{loaded}^2 - w_{unloaded}^2\right)$$

Same as the LTE calculation, if the FWD is approaching a joint/crack, w_{unload} = w_1 and w_{loaded} = w_0. If FWD is leaving a joint/crack, w_{unload} = w_7 and w_{loaded} = w_0.

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